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PREPARATORY REPORT OF PRESSURIZED FLUIDIZED BED COMBUSTION

**The University of British Columbia
Vancouver, B.C. Canada**

PREPARATORY REPORT OF
PRESSURIZED FLUIDIZED BED COMBUSTION

by

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Abstract

Pressurized fluidized bed combustion is a promising technique for burning coal efficiently and cleanly for generation of electrical power or co-generation of power, steam and heat. Small scale and pilot plant scale (up to 85 MW_{th}) PFBC units have been operated and are under construction in a number of countries, with England, the U.S., Sweden and Germany playing leading roles.

Visits to key facilities have confirmed that pressurized fluidized bed combustion is a feasible and attractive technique. In terms of combustion efficiency, sulphur capture, NO_x emission levels, heat transfer and temperature uniformity, PFBC units have generally performed up to expectations. Some problems have been encountered with particle feeding and withdrawal, tube wear, hot gas clean-up and erosion/corrosion/deposition for turbine blade tests elements. Further work is needed in all of these problem areas, but none of the difficulties appears to offer insurmountable technical obstacles to the commercialization of PFBC. Other areas such as sorbent regeneration, circulating pressurized fluidized bed combustion, and advanced cycles could also lead to significant advances.

No experimental PFBC work has been carried out in Canada. However, British Columbia Hydro has had coals and sorbents tested in England and continues to have an active interest in building a PFBC power plant to burn Hat Creek coal. Other electrical utilities in Canada do not express immediate interest in PFBC at this time, but a number of provinces are likely to develop interest if electricity demand begins to grow again and if PFBC can be demonstrated to be technically and economically viable. Strategies for Canada in the PFBC field are outlined, and it is proposed that an active research program should be launched in areas that complement work in progress in other countries.

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1. INTRODUCTION

1.1 Pressurized Fluidized Bed Combustion

Fluidized bed combustion was developed in the 1960's by the National Coal Board in England as a promising new technique for burning a wide range of solid fuels in a flexible, efficient and environmentally acceptable manner. Since that time, there has been widespread interest in developing fluidized beds for industrial uses and as a means of generating electrical power. Shortages and price increases of oil through the 1970's accelerated the development of fluidized bed boilers. In 1983 there are a number of companies offering packaged fluidized bed boilers and heaters on a relatively small scale, while fluidized bed combustors of various types are in wide usage, especially in Europe and China, for district heating and waste incineration.

For the smaller scale operations (generally less than about 25 MW) discussed in the previous paragraph, the fluidized beds operate effectively under near-atmospheric pressure conditions, giving what is called atmospheric fluidized bed combustion (AFBC). For electric power generation, on the other hand, there are significant additional advantages of operating at higher pressures (generally 10 to 20 bar) giving what is called pressurized fluidized bed combustion (PFBC). The latter is the subject of this report. Advantages of PFBC over AFBC include further gains in compactness and control of gaseous emissions, a reduction in the number of solid feed points required, and suitability for combined cycle operation leading to improved thermal efficiency in power generation.

The first pilot plant pressurized fluidized bed combustor came into operation at Leatherhead, England in 1969. Since that time small scale and test PFBC facilities have been built and operated in a number of countries. While problems have been encountered with individual components in each of the facilities tested, these problems have generally been solved without major difficulties. While further tests are needed, especially on gas turbines operated on the off-gases from fluidized bed combustors, there seems little doubt that PFBC technology will be applied to large-scale power generation within the next decade. This report provides an overview of the principal work which has been carried out in the world on pressurized fluidized bed combustion and on the critical areas in which further work is required.

1.2 Background of this Study

While interest has been shown in Canada, notably by British Columbia Hydro, in PFBC, and there have been some Canadian activities in the AFBC area (1), there are no experimental facilities for PFBC research in Canada. After consultation with Energy, Mines and Resources Canada, B.C. Hydro and a number of other organizations, a group in Chemical and Mechanical Engineering at the University of British Columbia (UBC) submitted a detailed proposal to the Canadian government in August 1981 for the construction and operation of a PFBC facility at UBC. This proposal was received favourably by the government of Canada, but the group was urged to seek a component (approximately 25%) of the funding

from industry and from British Columbia. Contributions were promised from several groups, but B.C. Hydro's share was made contingent on receiving a matching grant from the Energy Development Agency of the British Columbia Provincial Government. Although this agency has had this proposal since February 1982, and we understand that the proposal has been reviewed positively by the agency, no decision (positive or negative) has ever been taken on the proposal. Hence the proposed facility at UBC has not been able to proceed even though it has received wide support.

Given the impasse in the proposal, the UBC group, after further consultation with Energy, Mines and Resources, submitted a further proposal in late June, 1982 for preparatory work related to pressurized fluidized bed combustion. This would allow updating of the previous literature survey and background work to enable the most critical problems and areas of research to be identified. No equipment was to be purchased or constructed, but the background was seen to be important in any subsequent design and construction work. The report to be produced would also provide background information and advice to the Canadian government in planning research and development in the PFBC area.

The preparatory study was funded in early October, 1982. The present report gives the findings and recommendations which have resulted from the study.

1.3 Specific Objectives of this Study

The specific objectives of the preparatory study were identified in the June 1982 proposal as the following:

- (1) To provide an up-to-date review of available literature on pressurized fluidized bed combustion.
- (2) To discuss the current state-of-the-art with leading specialists and to visit key installations in other countries in order to define the current situation and to identify pitfalls and promising approaches.
- (3) To identify perceived needs in Canada through discussions with the Government of Canada, with the provincial utilities, and with the private sector.
- (4) To prepare a report which would provide details of the findings. The report would further identify those areas which will require research before PFBC can be applied successfully in Canada.
- (5) To prepare a further proposal, including detailed costs, for a PFBC facility to operate in Canada and for an experimental program which will cover the research needs identified.

The current report covers objectives (1) to (4) above. A further proposal for specific work to be undertaken at UBC will be covered in a separate document to be submitted shortly as an "Unsolicited Proposal".

2. CURRENT STATUS OF PFBC DEVELOPMENT OUTSIDE CANADA

2.1 Literature Overview

A complete listing of references on fluidized bed combustion, atmospheric and pressurized, was compiled in 1982(2). A technical evaluation of PFBC published by the Argonne National Laboratory (3) provides a valuable summary of information published in 1980 and earlier. In Table 1 we present a survey of nearly 200 papers and reports dealing directly with one or more aspect of PFBC. Publications have been categorized according to the principal topics addressed. It must be recognized that this tabulation does not cover a host of papers which treat related aspects such as AFBC or hydrodynamics and heat transfer of pressurized fluidized beds.

From the extensive list in Table 1 it is clear that there has already been a considerable research effort in the PFBC area. In general, it is fair to say that experimental PFBC systems have performed up to expectations from a number of points of view, but that problems remain to be solved with a number of components.

Areas where experimental and demonstration units have generally given good performance include:

(a) Combustion efficiency: Because of the relatively deep beds used for PFBC, underbed feeding of coal, excess air usually exceeding 10%, and increased oxygen partial pressures at high pressure, combustion efficiency has generally been very favourable, typically 98% or above, even without recycling of fines from the cyclones.

(b) Sulphur capture: Despite some predictions to the contrary (188), it has proved to be possible to capture sulphur in pressurized beds with approximately the same efficiency as in atmospheric units providing that dolomite rather than limestone is used as sorbent. Typical results (168) show 90% sulphur capture by dolomite at a Ca:S ratio of about 1.6 over a pressure range from 6 to 20 bar.

(c) NO_x emissions: NO_x emissions have tended to be much more sensitive to excess air levels than to the pressure in the bed over a range up to 20 bar (168). Measured levels have satisfied emission standards (3) even at excess air levels as high as 100%.

(d) Heat transfer and temperature uniformity: Fluidized beds have favourable heat transfer coefficients, and increased pressures serve to enhance heat transfer further. For typical PFBC conditions, heat transfer coefficients tend to be 10-20% greater than in corresponding ABFC units. Good temperature uniformity is also maintained providing that heat transfer tubes are not so close together that they prevent particles from circulating freely through the tube bank (as in the first tube bank configuration employed at Grimethorpe).

Specific areas where significant problems have arisen or where experimental verification is required before reliable large-scale PFBC systems can be built are discussed in detail in Chapter 3.

TABLE 1 - SUMMARY OF PUBLISHED LITERATURE ON PRESSURIZED FLUIDIZED BED COMBUSTION

Ref. No.	Author, Organization	Yr.	Combustion	Sulphur Capture	NO _x	Heat Transfer	Erosion/Corrosion	Cycles	Hot gas clean-up	Hardware	General review	Others
4	Lane, FCCL	81					x				x	
5	Hoy, CURL	81										
6	Wang, USA	81										
7	Moore, DOE	81										
8	Roberts, CURL	81	x	x	x		x		x			particle measuring probe
9	"	81	x	x	x				x			
10	"	81	x	x	x				x			
11	"	81	x	x	x				x			
12	Ulerich, WEC	81		x								
13	Ciliberti, WEC	81							x			
14	Johnson, ANL	81							x			
15	Hoke, Exxon	81	x	x	x		x		x			High temp valve Boiler
16	Kaden, IEA	81										
17	Robertson, FW	81		x								
18	Jahnig, Exxon	79		x								
19	Pillai, CURL	80							x			
20	Anon, GW	81	x			x			x			
21	Hoy, CURL	81										
22	Johnson, ANL	80		x					x			
23	Roberts, GE	80		x			x					
24	Mathers, IRC	80						x				
25	Grey, GE	80					x					
26	Janason, S-L	80					x					
27	Mogul, CW	80					x					
28	Spengler, WRD	80										
29	Keairns, WRD	80		x					x			
30	Hoke, Exxon	80							x			
31	Roberts, GE	80										
32	Johnson, ANL	80							x			
33	"	80							x			
34	"	80							x			
35	Hoke, Exxon	80										
36	Kaden, IEA	80		x	x							
37	Slaughter, EPRI	80										

TABLE 1 - SUMMARY OF PUBLISHED LITERATURE ON PRESSURIZED FLUIDIZED BED COMBUSTION

Ref. No.	Author, Organization	Yr.	Combustion	Sulphur Capture	NO _x	Heat Transfer	Erosion/Corrosion	Cycles	Hot gas clean-up	Hardware	General review	Others
66	Huber, BR	78						x				Particle segregation
67	Pillai, CURL	77							x			
68	Ciliberti, WRD	77						x				
69	Schilling, BF	77						x				
70	Brooks, GE	77						x				
71	Moskowitz, CW	77										
72	Ruth, Exxon	77		x			x					
73	Zellers, NASA	77							x			Particulate sampling probe
74	Yamamura, JCMRC	77										
75	Masters, ACX	77										
76	Hoy, CURL	77	x	x						x		
77	Podolski, ANL	77										
78	Priem, NASA	77					x		x			
79	Nutkiss, Exxon	78								x		
80	Wang, GE	77										
81	Zellers, NASA	78					x				x	
82	Singh, CW	79										
83	Schilling, AGW	78										
84	McCarron, GE	78					x					
85	Hoke, Exxon	78		x					x			
86	Johnson, ANL	78						x				
87	Huber, BR	78						x				
88	CW	77										
89	Jansson, S-L	82										
90	Schilling, BFFT											
91	NRDC	77	x	x	x							
92	CW	78										
93	CW	78						x				
94	CW	78										
95	CW	78										
96	Klett, GIL	77										

TABLE 1 - SUMMARY OF PUBLISHED LITERATURE ON PRESSURIZED FLUIDIZED BED COMBUSTION

[illegible]

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Ref. No.	Author, Organization	Yr.	Combustion	Sulphur Capture	Heat Transfer	Erosion/Corrosion	Cycles	Hot gas clean-up	Hardware	General review	Others
129	Hoy, CURL	79								x	Instrument
130	Zoll, CW	78									
131	Brooks, GE	79					x				
132	Morrow, PCR	79					x				
133	Allen, BCL										
134	Moskowitz, CW	78		x			x				
135	Hoke, Exxon	77	x								
136	Huber, B&R	77					x				
137	Huber, "	78					x				
138	Moskowitz, CW	80				x	x	x	x	x	
139	Graves, ORNL	82	x	x	x	x	x	x			
140	Boerick, GE	80				x					
141	DOE	82				x					
142	Rubow, GIL	82		x		x	x	x	x	x	
143	Crouse, MITR	82					x				Circulating PFBC
144	Zaharchuk, GIL	82									
145	Saari, FLD	82						x			
146	Hoke, Exxon	77	x	x					Oxygen probe		Status report
147	Rollbuhler, NASA	82	x					x			Coal feeding
148	Roberts, CURL	82	x				x				Status Report
149	Johnson, ANL	78		x							"
150	"	80		x							
151	Bierl, DOE	80									
152	Henry, ANL	82					x				
153	Fee, ANL	80		x							
154	Miller, NYU	81									Bed expansion
155	Miller, NYU	77			x						
156	Suter, BBC	82				x		x			

Ref. No.	Author, Organization	Yr.	Combustion	Sulphur Capture	NO _x	Heat Transfer	Erosion/Corrosion	Cycles	Hot gas clean-up	Hardware	General review	Others
157	Mukherjee, BBC	82						x				
158	Berman, WEC	82						x		x		
159	O'Connell, AEP/S-L	82						x	x	x	x	Scale-up
160	Moskowitz, CW	82						x		x	x	
161	Borden, GIL	82						x				
162	Rubow, GIL	82						x				
163	Jansson, S-L/AEP/CURL	82		x								CO ₂ effects
164	Markel, DOE	82							x			
165	Smith, IEA	82									x	
166	Wright, IEA	82								x		Teething troubles
167	Ljungstrom, CU	82								x		
168	Hoy, CURL	82			x					x		
169	Ciliberti, WEC/BR	82	x	x								
170	Zaharchuk, GIL	82							x			
171	Alvin, WEC	82							x			
172	McCarron, GE	82							x			
173	"	82					x					
174	Stringer, EPRI	82					x					
175	Vogel, ANL	75			x							
176	Vogel, ANL	75	x	x	x							
177	Carls, ANL	75		x						x		
178	Hoke, Exxon	75								x		
179	Moskowitz, CW	77									x	
180	Anon, WEC	81							x			
181	Patch, NASA	79							x			
182	Nutkiss, Exxon	79										
183	Henry, ANL	81					x		x			
184	Hoke, Exxon	80	x	x	x		x		x			Status Report
185	Rollbuhler, NASA	81										
186	Rollbuhler, NASA	80							x			
187	Kobak, NASA	81								x		
188	Newby, WRD	80										
189	Judd, Natal	80		x						x		Multistaged Applications
190	Harboe, S-L	80									x	

TABLE 1 - SUMMARY OF PUBLISHED LITERATURE ON PRESSURIZED FLUIDIZED BED COMBUSTION

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Ref. No.	Author, Organization	Yr.	Combustion	Sulphur Capture	NO _x	Heat Transfer	Erosion/Corrosion	Cycles	Hot gas clean-up	Hardware	General review	Others
191	Hoke, Exxon	80							x			
192	Roberts, CURL	80					x			x		Dust sizing
193	Jansson, S-L	81							x			

Abbreviation of Organisations

ACX	-	Acurex Corporation, USA	GE	-	General Electric, USA
AEP	-	American Electric Power	GIL	-	Gilbert/Commonwealth Associates, USA
AGW	-	Arbeitsgemeinschaft Wirbelschichtfeuerung	IEA	-	International Energy Agency (at Grimethorpe), UK
ANL	-	Argonne National Laboratory, USA	IRC	-	Ingersol Rand Company, USA
BBC	-	Brown Boveri & Company, Ltd., Switzerland	JCHRC	-	Japan Coal Mines Research Centre, Japan
BCL	-	Battelle Columbus Laboratory, USA	MITR	-	MITRE Corporation, USA
BF	-	Bergbau-Forschung, W. Germany	NASA	-	NASA Lewis Research Centre, USA
BPFT	-	Bundesministerium fuer Forschung und Technologie	NATAL	-	University of Natal, South Africa
BR	-	Burns & Roe Industrial Services Corp.	NRDC	-	National Research Development Corporation, UK
CU	-	Chalmers University of Technology, Sweden	NYU	-	New York University, USA
CURL	-	Coal Utilisation Research Laboratory, UK	ORNL	-	Oak Ridge National Laboratory, USA
CW	-	Curtiss Wright, USA	PCR	-	Preece Cardew and Rider, UK
DBA	-	Deutsche Babcock Anlagen, W. Germany	S-L	-	Stal-Laval Turbine AB, Sweden
DOE	-	Department of Energy, USA	SUNY	-	State University of New York, USA
EXXON	-	Exxon Research & Development Centre, USA	UTC	-	United Technical Corporation, USA
FCCL	-	Fluidised Combustion Contractors Ltd., UK	WEC	-	Westinghouse Electric Corporation, USA
FLD	-	Fluidyne Engineering Corporation, USA	WRD	-	Westinghouse Research & Development
FW	-	Foster Wheeler Development Corporation, USA			

2.2 Site Visits

As part of this contract, visits were made to key centres where PFBC work is in progress. The visits covered three countries (England, Sweden and the United States) with additional involvement from Germany in several of these projects. The sites visited represent government laboratories (Argonne, CURL, IEA Grimethorpe and NASA Lewis Research Centre), industry (Curtiss-Wright, Exxon, General Electric, Stal-Laval), and universities (Cambridge, Chalmers, and New York University). The centres visited represent the principal PFBC centres in the world both from a historical point of view and in terms of current expertise and activity.

Reports on the site visits are given below in alphabetical order. These reports provide some general picture of the work in progress, the experimental facilities, and the general perspectives of key personnel on the future of pressurized fluidized bed combustion.

2.2.1 Site Visit to Argonne National Laboratory, Argonne, Illinois

The Argonne Laboratory is one of the national laboratories of the United States federal government. It is divided into a large number of energy-related divisions. The Chemical Engineering Division is one of these. The fluidized bed combustion group comes under the fossil fuel group of this division. Presently it operates under contract from the Morgantown Energy Centre of the Department of Energy.

ANL started its work on pressurized fluidized bed combustion in 1973-74. The objectives of their work have changed over time depending upon funding agency priorities. Investigations have treated:

- i) The effect of variations of bed temperature, gas fluidizing velocity, and sorbent feed rate on sulphur retention, effluent NO_x level, combustion efficiency and particle elutriation rate;
- ii) Criteria for selection of solid sorbent;
- iii) Regeneration of partially sulphated sorbents;
- iv) Collection efficiencies of granular-bed filters and TAN-JET cyclones.

Experimental Facilities

A schematic diagram showing the various components is shown in Fig. 2.1.

(a) Coal feed System:

Coal is fed manually into a carbon steel vessel ($\approx 1' \times 3'$). There is a pressurizing vessel below this bunker separated by two ball valves. The lower vessel is pressurized with bypass air from the compressor. It is supported on load cells. Bridging at the entry to the drop pipe has been a problem.

A rotary air lock feeder (by Baueumont Birch, Pennsylvania) feeds coal from the vessels. Problems have occurred if the coal was too fine or moist. The nylon scraper blades on the feeder have had to be replaced at times. The pressure in the lower vessel is kept 2-5 psi above that of the transport line. The feeder rotates at about 10-12 rpm and is controlled by a thyristor element supplied by the same company. In order to prevent air leakage across the feeder gland, high pressure air is provided on the glands.

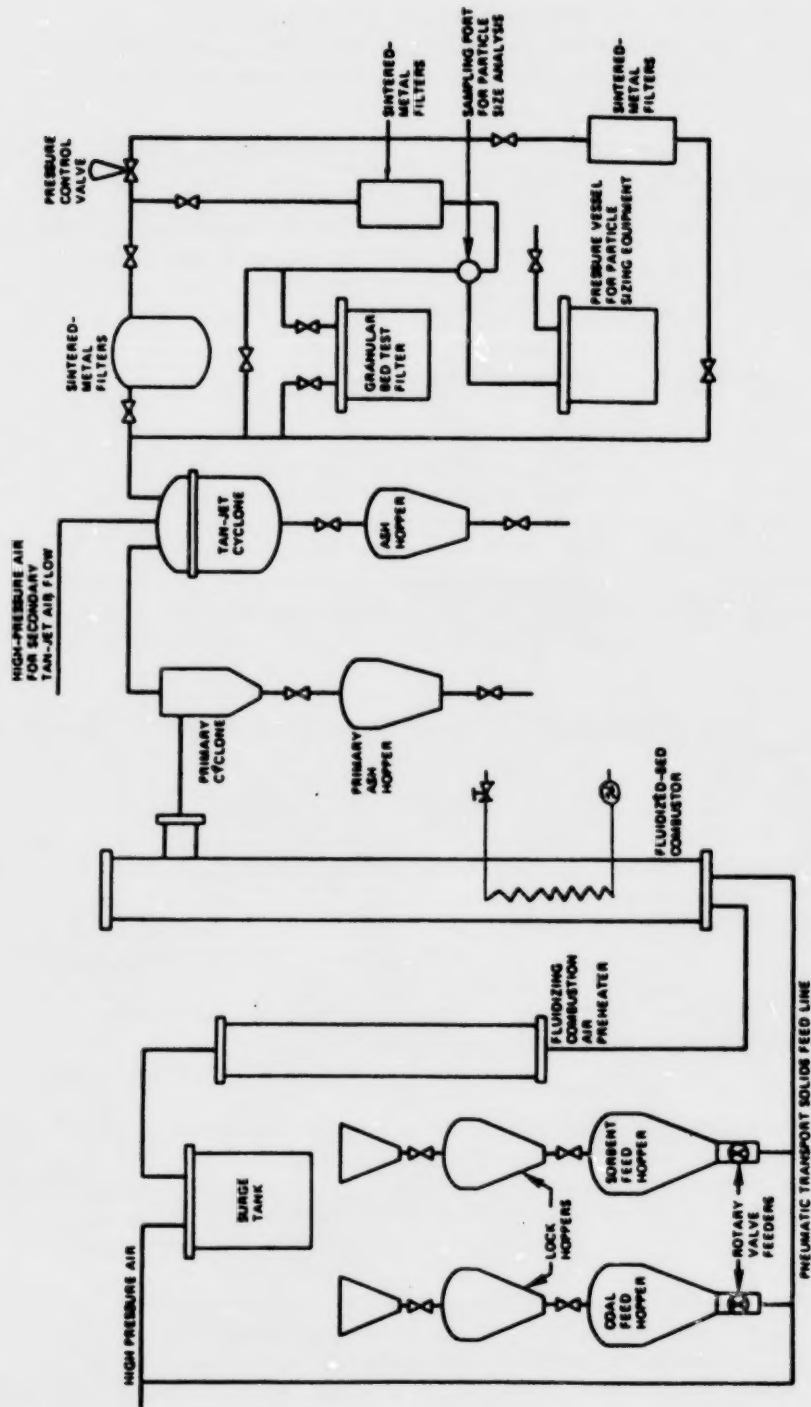


Fig. 2.1: Schematic Flow Sheet of Argonne PFBC System

The transport line is a 1/2" SS tube. The transport air velocity is 30-50 ft/s.

(b) Column

The total height of the column is 104". It is made of schedule 40, 18" pipe (carbon steel). Heavy forged (2") flanges have been used. It has two sections, the first being 48" long and the top section 56" long. There are two layers of refractory, a hot face insulation (KL Mix by Plibrico), then verilite insulation.

The bed is 32" deep and has an overflow pipe at this level. This column has series of sampling ports.

The air plenum chamber is a stainless steel vessel (6"ID x 20" approximately) encased in another carbon steel vessel (18"OD x 40 sch). The annulus is filled with insulation. The bottom flange is heavy (as per ASME) and forged. Tubes for the feed, ash drop line and air inlet are all welded to this. The distributor is welded to the top of the inner SS tube.

The distributor is a 1/2" thick SS plate with 8 bubble caps. Each cap has 6 holes (1mm Φ). Holes are inclined downwards towards the plate. These inclined jets caused some erosion of the plate. Severe plugging of the annulus due to fused inerts has also occurred.

Two rupture disks are provided in series. A pressure signal actuates an alarm before the second disk. The vent pipe is a 3" Φ pipe passing to the roof via a catch pot to capture debris in the event of an explosion.

(c) Cyclones

There are three cyclones connected in series. The first cyclone is refractory lined with an inside diameter of 4" and an outside diameter of 12". It is made of carbon steel. The second cyclone has an inside diameter of 2". This cyclone is water cooled by copper tube wrappings.

These cyclones have operated effectively, with only a marginal amount of dust collected in the 3rd cyclone. In a number of tests, the second cyclone was replaced by a TANJET (proprietary) cyclone. The performance was found to be satisfactory.

(d) Gas Sampling

A 1/2" pipe collects gas samples. Gas first passes through a Graham Heliflo surface condenser, then through a pressure regulator to the sampling instruments. Gases are analysed on-line for O₂, CH₄, CO₂, CO hydrocarbon, NO_x and SO₂.

(e) Cooling Coil

There are five U-shaped coils, each made of 3/8" OD tube with longitudinal fins and extending a distance of 38" down to 10" above the distributor. There are two semicircular ring headers, one for inlet water and the other for outlet water. The coils are welded to an intermediate flange. The water inlet and outlet temperatures are measured at a control panel. The water flow is varied to control the bed temperature. Distilled water has been used in most cases. It is cooled in an external heat exchanger (glycol medium).

(f) Support structure

The whole column is suspended from the top. This allows sufficient room for expansion. At mid-section provision for bolting up to the main structure has been made. This could be utilised during maintenance.

(g) Solids discharge

The bed overflow pipe is a lock hopper. Hot solids accumulate in this uninsulated shell, supported on two springs to allow for thermal expansion of the entire section.

2.2.2 Site Visit to Cambridge University, England, January 29, 1983

J. F. Davidson, Shell Professor of Chemical Engineering at Cambridge, is supervising work in a 10 cm diameter PFBC unit at the Rutherford (government) labs near Harwell. The laboratory is principally concerned with large-scale physics equipment (e.g. accelerators) and has had no problem coping with the PFBC unit. Prof. Davidson feels that the cooperative arrangement, whereby all practical details of installing and maintaining the equipment have been looked after by a group external to the university, has been excellent.

The unit itself can operate up to 17 bar pressure. It is suspended in a pressurized shell with refractory on its inside. The inner column is heated by an electrical coil for single particle burnout studies.

Tests have been carried out similar to those described by Avedesian, only at elevated pressures. An Australian student named Turnbull is doing this work. Their results show a decrease in burnout time as the pressure increases from 1 to 7 bar, but the time levels out and is essentially constant from 7 to 17 bars since film diffusion becomes the rate-limiting step, with $D \propto p^{-1}$ and $C_A \propto p$.

The cost of the equipment, including instrumentation and installation, but excluding all subsequent operating costs, was approximately £250,000.

Future plans with the PFBC rig include completion of the single particle burnout work, study of particle efflux rates from pressurized beds, and the unsteady response of temperature and concentrations to cycling of the solids feed rate. Some work may also be done on entrainment at elevated pressures.

Prof. Davidson did not know of any other university PFBC work in the UK. He did mention AFBC work at Sheffield and Leeds. Some AFBC work may also be planned at Birmingham. Cowley at Shell is doing some small-scale AFBC work. There appears to be wide acceptance in industry of medium size AFBC units.

2.2.3 Site Visit to Chalmers Technical University, Goteborg, Sweden
Feb. 2, 1983

Introduction

Talks were held with the following persons:

Professor Erik Olsson and Mr. Almstedt, Department of Thermo and Fluid Dynamics
Professor Bo Leckner and Mr. Sven Andersson, Department of Energy Conversion
Professor Evert Ljungstrom, Department of Inorganic Chemistry,
(holds cross-appointment with University of Goteborg)

This group has become active in gas sampling, solids sampling and in situ hydrodynamic measurements in the Leatherhead 0.3 m square bed described earlier. They have also been instrumental in procuring for their university an atmospheric 2 m square fluidized bed boiler which supplies heat and steam to the university and surrounding area. In addition, they have a 0.7 m square AFBC unit and a 0.7 m x 0.07 m cold model unit. They do not currently own any PFBC unit themselves, but are hoping to obtain a pressurized shell with sight glasses in which they can install columns to operate at high pressure. In addition to technical discussions, the visitor (JRG) gave a seminar to a group of about 20 on activities at UBC.

PFBC In-Bed Gas and Solids Sampling and Hydrodynamics

This work is being carried out by Prof. Ljungstrom and A. Almstedt. Some data were reported at the 7th International Fluidized Bed Combustion Conference (167,196) in Philadelphia. The work is sponsored by the Swedish government (National Swedish Board for Energy Source Development). Further data were obtained recently at four different positions inside the 20 bar PFBC unit at Leatherhead. All probes have been designed to fit through the 25 mm tube openings provided on the side of the bed and can be located at different horizontal and vertical positions. Probes which have been developed are as follows:

- (a) Zirconia cell used to measure local oxygen concentrations: The cell, described in detail in ref. 167, has a rapid response time (approx. 20 ms), but is somewhat sensitive to variations in temperature and to collisions by particles. It clearly shows local oxygen excursions due to uneven coal feeding as well as mean concentration differences between two levels and between the centre and corner regions at a given level.
- (b) Gas sampling probe connected to GCMS: This probe, also described in ref. 167, consists of a pin hole aperture with a screen to prevent solids entry and heating to prevent condensation. The system is suitable for measurements of SO₂, NO, NO₂, CO₂ and O₂ but fails to give good results for CO (since this is masked by N₂) and for SO₃ (due to condensation problems).
- (c) Double capacitance probe: Several different probe geometries have been tried. The one adopted has two horizontal shielded projecting

wires separated by 15 mm with the top one extending slightly further than the lower. Details are given in ref. 196. Cross-correlation of the signals from the two wires provides a measure of bubble velocity and pierced length as described by Werther for beds operated under atmospheric conditions.

- (d) Solids sampling device: This device, also described in ref. 167, allows grab samples to be taken at different positions. It has been used also in the atmospheric boiler described below.

AFBC 2 m Square 16 MW_{th} University Boiler

While not a PFBC unit, this installation is a notable achievement. It replaces an old coal-fired stoker boiler and provides a demonstration unit, a place for training operators, and is designed to allow the research workers to obtain useful data. Due to space restrictions and an existing coal bunker, the equipment had to be adapted somewhat to fit within the available space. Various coals have been used with a local limestone as sorbent. Horizontal tubes are used for cooling. The bed operates with a bed height of about 1 m, and at superficial velocities of 1.5-2.5 m/s. There are two stages of cyclones. The bed is fed at the top in one corner, but still appears to work well suggesting that the common criterion of 1 feed point per square metre may be overly conservative. For reduced loads, the superficial velocity is first reduced as far as 1.5 m/s; for further load reductions part of the bed is slumped. Extensive details of this facility are provided in ref. 197.

AFBC 0.7 m square experimental unit

This was an early unit constructed with minimal funds. Nevertheless, the scale is impressive. The unit is not used very much at this time, although there are plans to use it for measurements of heat transfer coefficients to tubes in the freeboard region.

Cold Model 0.7 m x 0.07 m unit

This is meant to simulate a section of the 0.7 m square bed. There are nine bubble cap distributors. It is being used to study load following, with air to five of the caps being turned off. Theoretical modelling using a vector form of the Ergun equation is also being used.

Other Reported Work in Sweden

It was reported that relatively small AFBC beds are selling well in Sweden for district heating. In addition circulating beds are being marketed by Ahlstrom, Studevick, and Gotaverken. The latter is also reported to be building a pressurized circulating bed. We were unable to arrange an interview with them.

2.2.4 Visit to Coal Utilization Research Laboratories, Leatherhead,
U. K., Jan. 31, 1983

The day was spent with Allan Roberts and John Stanton who were most helpful. Raymond Hoy was away the day of the visit.

BCURA has been active since 1938 as a research association for the coal industry. Activities were centralized at Leatherhead from 1948. From 1970 when NCB research activities were consolidated at Stoke Orchard, the Leatherhead operation has become entirely self-financing through contract work. It has played a major role in the development of fluidized bed combustion, especially PFBC.

The laboratory has extensive facilities for pilot plant scale work, cold model studies, hot gas clean-up etc. Of special note are three PFBC rigs:

- (a) 2 ft x 3 ft column built in 1969 and used for many of the early PFBC experiments. It has been idle for the past two years but could still be used. Its maximum pressure is 6 bar. A diagram appears in Fig. 2.2.
- (b) 12 inch diameter column in use since 1975. This is an unsophisticated piece of equipment which has been extremely useful for a whole series of experiments. A diagram appears in Fig. 2.3.
- (c) 12 inch square column completed in 1981. This is more sophisticated with provision for sampling at various levels and changing the configuration of tube bundles as well as many common features with the earlier columns such as the methods of solids feeding and withdrawal. This bed can withstand operating pressures up to 20 bar allowing a considerable extension of the range of conditions studied in earlier work. The total cost, excluding compressor and control room, was approximately £250,000. The cost was shared between American Electric Power (with Stal-Laval and Babcock Werke), the Swedish Department of Energy, the Electric Power Research Institute (U.S.), and CURL. This combustor is shown in Fig. 2.4.

Many details of the three columns are presented in Table 2, in section 2.2.12 below.

Much of the work done by the Leatherhead group has been of a confidential nature. The principal contributions have been in the following areas:

- first studies of PFBC;
- background design information for Grimethorpe and several other larger installations;
- tests on a wide variety of coals over a range of conditions showing the feasibility of PFBC;
- extensive measurements of heat transfer, entrainment, and combustion efficiency;

1. Compressed air inlet
2. Water inlets and outlets to tube bank circuits
3. Baffle tubes in freeboard
4. "High level" bed offtake
5. Tube bank
6. Start-up burners
7. Coal nozzle
8. Air distributor
9. Bed offtake
10. Corrosion probes
11. Air cooling supply to corrosion probes
12. Gas offtake baffle
13. Mixing baffle
14. Gas splitter
15. Corrosion indicator probes
16. Zirconia-cell oxygen probes

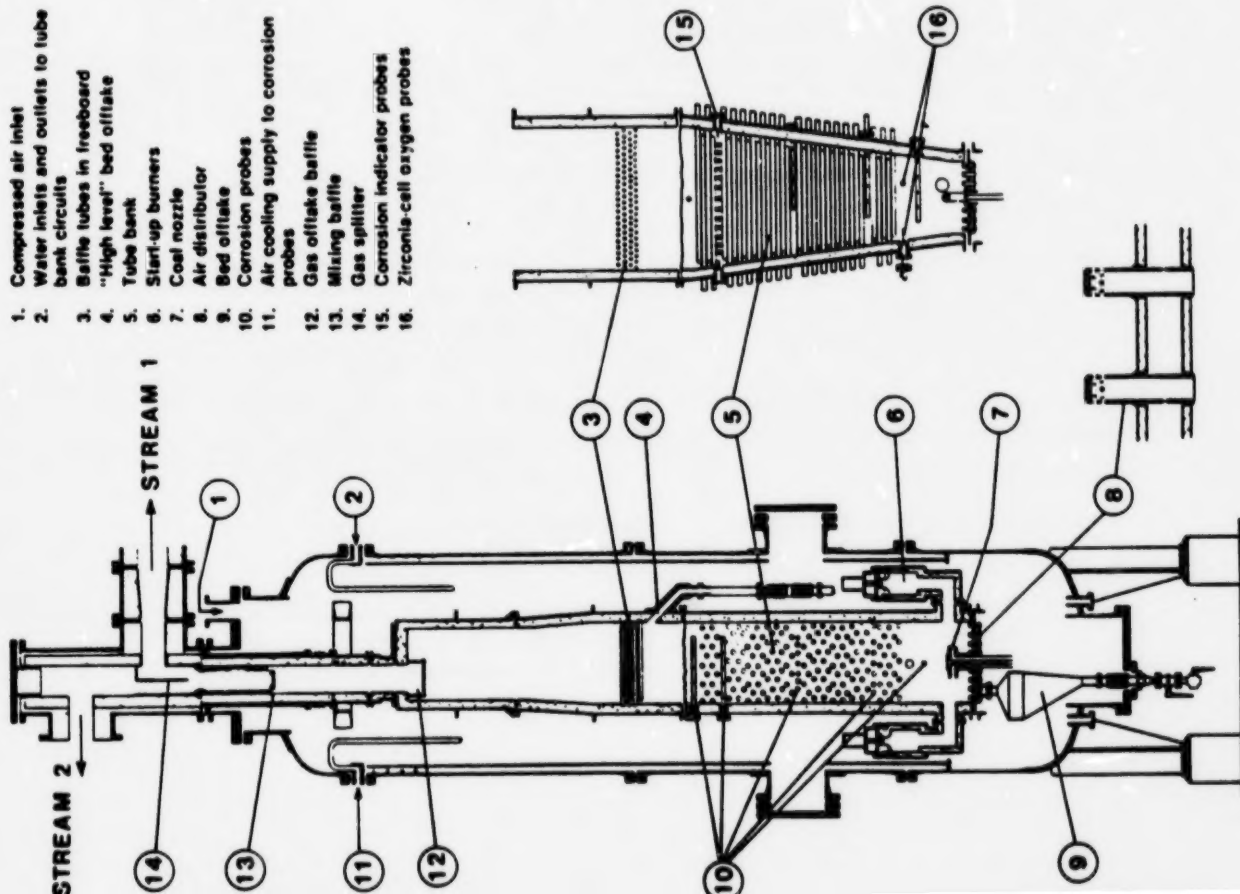


Fig. 2.2: CURL 2 ft x 3 ft Combustion Column

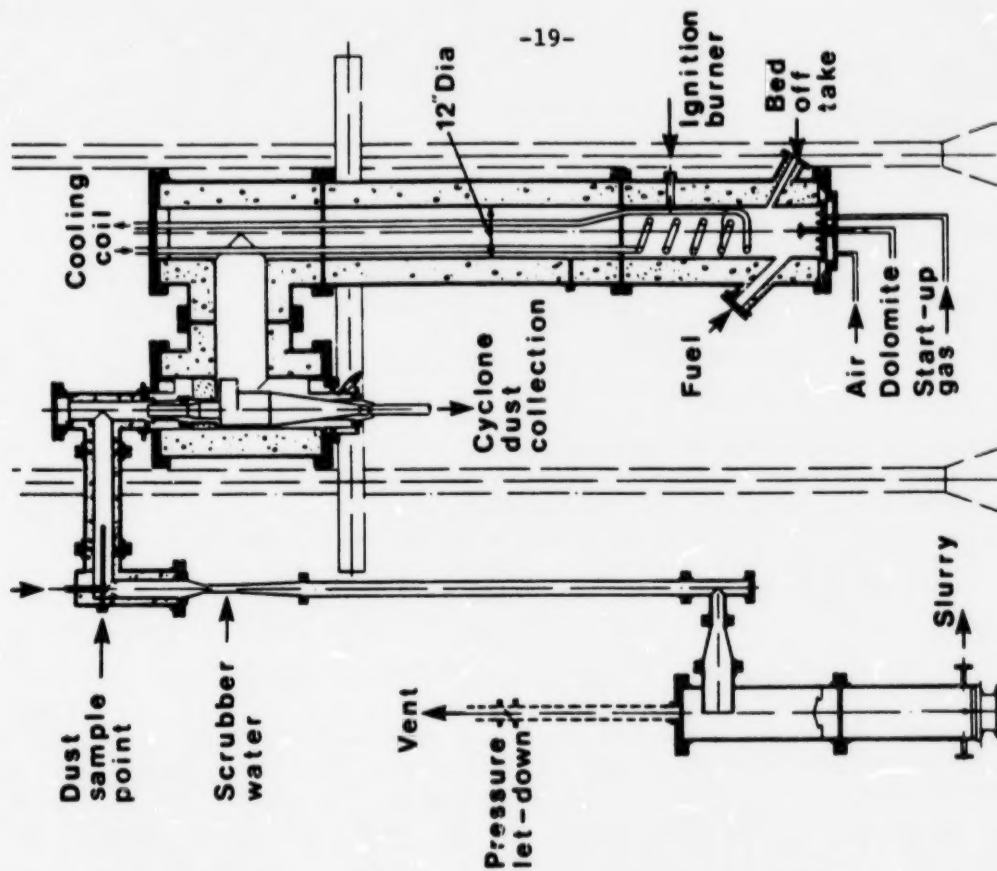


Fig. 2.3: CURL 12 inch diameter Combustion Column

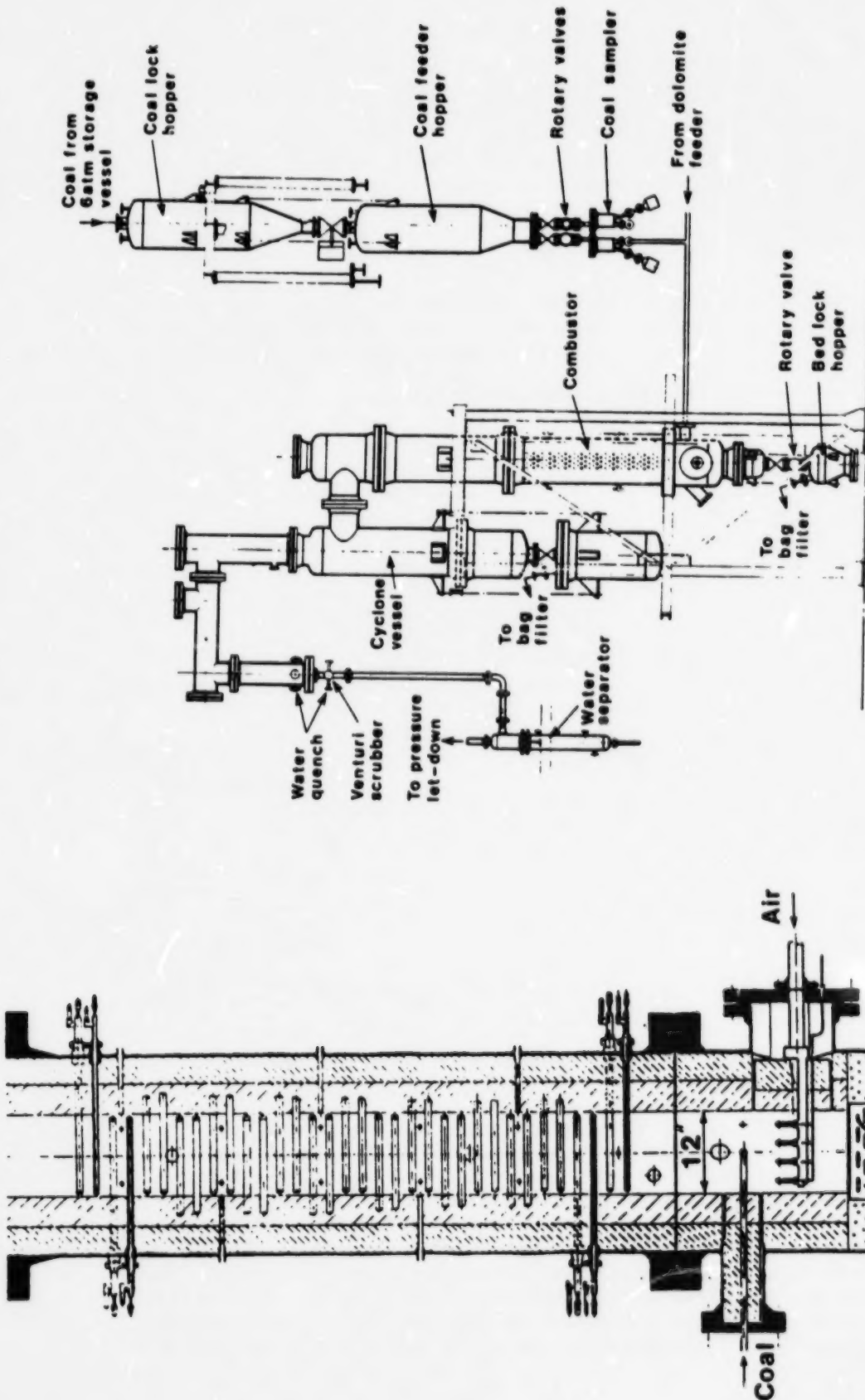


Fig. 2.4: CURL 1 ft square 20 bar PFBC Facility showing Tube Arrangement, Feed System, Ash Withdrawal etc.

- extensive work on sulphur capture, sorbent preparation and behaviour, and mechanisms of capture;
- corrosion work;
- measurement of SO_3 and alkali levels in off-gases;
- profiles of O_2 , CO , NO_x and SO_2 concentrations.

Current work in progress includes testing of Hat Creek coal with a B.C. limestone in the 12 inch square rig, burning of coal-water slurries (60-65% solids) in the 12 inch diameter column, and cold model studies using plastic tubes, pressure transducers and photography to investigate the mechanism and preventative measures for tube erosion (related to the problems at Grimethorpe). They will also test the burning of run-of-mine coals in the 12" dia. unit.

CURL recently put in a proposal to D.O.E. for some work on a pressurized fast fluidized bed. They would hope to base this on the 12 inch square column. They feel they have extensive experience circulating solids during their gasification work. They would especially like to study the heat transfer from downflowing solids in dense fluidization to an array of horizontal tubes.

Some of their perspectives regarding the future of PFBC are as follows:

- For reasons of cycle efficiency, costs, and tube materials problems, they do not believe that the Curtiss-Wright approach will be widely adopted. However, the turbine testing to be done by Curtiss-Wright is seen to be important.
- They are also pessimistic about the gasification route to power generation.
- They feel that the EPRI route using turbo-expanders has a good chance of success because components are being adopted which are well known. Hence risk is minimized and acceptance from the utilities should be favourable.
- Demonstration that turbines can operate on PFBC off-gases is again seen as the major problem in achieving wide acceptance of other PFBC routes.
- The erosion/corrosion problem at Grimethorpe is relatively new. While worrisome, it is not seen as a major hurdle.
- The downturn in the demand for electrical capacity and the preoccupation of the CEBG with nuclear power are seen as insuperable barriers to large-scale application of PFBC in the U.K. for some time.

- They are hopeful, but not too optimistic, that a way can be found to keep Grimethorpe operating beyond Phase I.

CURL recently cooperated with the Chalmers University group in some in-bed measurements. Zirconium probes and capacitance probes were immersed in the 12 inch square bed at four positions to measure profiles of oxygen concentration and bubble size. The results are still awaited at this time. (See report on Chalmers University visit.)

Results of the extensive work done on sulphur capture at Leatherhead will be written up this summer. John Stanton gave me a detailed account of this work. Key findings include:

- Dolomites are generally more effective than limestones as PFBC sorbents due to a more open structure and larger pores which can stay open as the larger CaSO_4 molecules are formed.
- Gradual calcining, e.g. with higher CO_2 levels, results in improved sorbent performance.
- Some improvement may also be achieved with additives such as iron.
- Components in the ash may give some sorption and some catalytic effects. Some refractories may also cause some sorption.
- SO_3 seems to play a key role. Its level in the bed appears to be low due to rapid reaction there, but the level increases above the bed, especially as the SO_2 and O_2 levels increase. Reactions with CO and NO_x may also be important, and ash constituents may play a role as catalysts.
- The quality of a particular dolomite or limestone as a sorbent cannot be predicted from the chemical composition or pore size distribution alone, although these can provide some general guidance.
- Some unsteady state response tests have been carried out in which the dolomite feed rate has been suddenly interrupted. While the SO_2 levels have responded rapidly, the SO_3 transient has been much longer. This finding has not been explained.

2.2.5 Site Visit to Curtiss-Wright Corporation, Wood-Ridge, New Jersey Dec. 15, 1983

The day was spent with Arthur Stappenbeck, senior program manager for power systems.

Curtiss-Wright has been active in PFBC technology since the early 1970's. A small PFBC Laboratory rig was built in 1974. In 1976 CW was awarded a multi-phase research contract by the US Department of Energy to design, construct, and operate a combined cycle pilot plant using the PFB concept for combustion of high sulfur coals. The contract involves:

- (i) conceptual designs for a 500 MW_e PFBC/CL power plant and a 13 MW_e pilot plant with the basic configuration of a commercial plant;
- (ii) a technology testing program using a small PFB rig to determine the design criteria and evaluate materials for the pilot plant;
- (iii) final design and construction of a pilot plant and a 2-year testing program.

A 0.92 m diameter PFBC Small Gas Turbine (SGT) test rig was built in 1977. A test program including 3000 h of experiments, 1000 h with the gas turbine in operation, using Pittsburgh high sulfur bituminous coal and Ohio pfizer dolomite was completed in 1979. This rig is presently being used for testing and evaluating of Acurex's ceramic felt bag, Research Cottrell's electrostatic precipitator and GE's electrocyclone. A 13 MW_e PFBC/CC pilot plant is now under construction and is expected to be completed before the end of the year. In addition, CW also operates a 3.05 m square AFB coal fired boiler plant in Shamokin, Pa.

PFBC/CC Power Plant Concept

The CW concept of a PFBC/CC power plant is to remove heat from the bed by heating air in an in-bed heat exchanger. The gas mixture, about two-thirds heated air and one-third hot-cleaned combustion off-gases, is expanded through a gas turbine to drive a compressor and an alternator. The gas leaving the power turbine enters a waste heat boiler, where steam is generated to drive a steam turbine. Approximately 60% of the total plant power is produced by the gas turbine and 40% by the steam turbine.

Small Gas Turbine (SGT) PFBC Test Rig

Specific details are presented in Table 2 and in Figs. 2.5 and 2.6.

The combustor has a diameter of 0.92 m and an expanded bed height of 4.94 m with a 4.6 m freeboard. It was designed to operate at 6.5 bar and 899°C and with 30% excess air. There are 9 vertical heat exchanger tubes in-bed. The gas turbine is Rover 1S/60, modified to have 21 individual investment stator vanes and 21 rotor blades. There are separate Petrocarb feeding systems for coal and dolomite. This rig is equipped with computerized control, a data logging system and gas analysis instruments.

In the early tests, the hot gas clean-up system consisted of one recycle cyclone and three ash removal cyclones. At the time of the visit, the second ash removal cyclone was being replaced by a Research Cottrell electrostatic precipitator, and the gas stream bypassing the gas turbine discharged into the atmosphere directly. A butterfly valve was used at the exhaust end to control the system pressure. An on-line particulate measurement system and an alkali measurement system by Sandia Laboratory and Ames Laboratory respectively were also added to the rig.

Early results from this rig were presented at the AIAA 19th Aerospace Science meeting in January, 1981 at St. Louis. Some key findings are:

- The NO_x emission was less than 0.091 kg/TJ (0.2 lb/10⁶ BTU) which was below the US EPA requirement. The SO₂ capture efficiency was 95% at a Ca/S ratio of 1.5 and was higher for Ca/S=2.0. The SO₂ emission at a 1.5 Ca/S ratio was less than 0.136 kg/TJ, again below the EPA requirement.

- The particulate loading of gas entering the gas turbine was about 100 ppm with a mean particle size of about 1.3 μm and a maximum size less than 10 μm; the sodium and potassium vapor was less than 1 ppm.

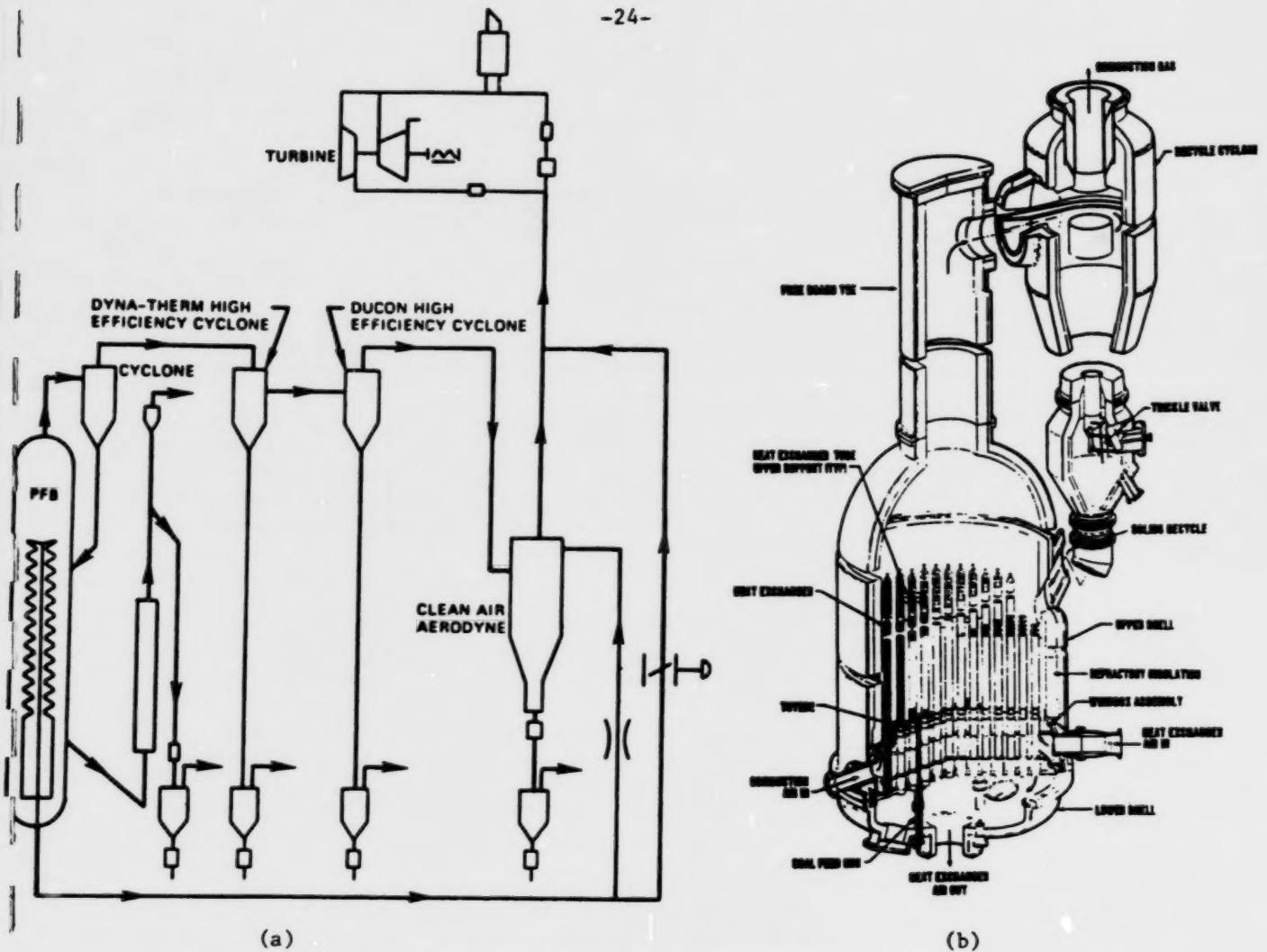


Fig. 2.5: Curtiss-Wright Facilities: (a) Small Gas Turbine (SGT) Technology Rig; (b) 13 MW_e Pilot Plant.

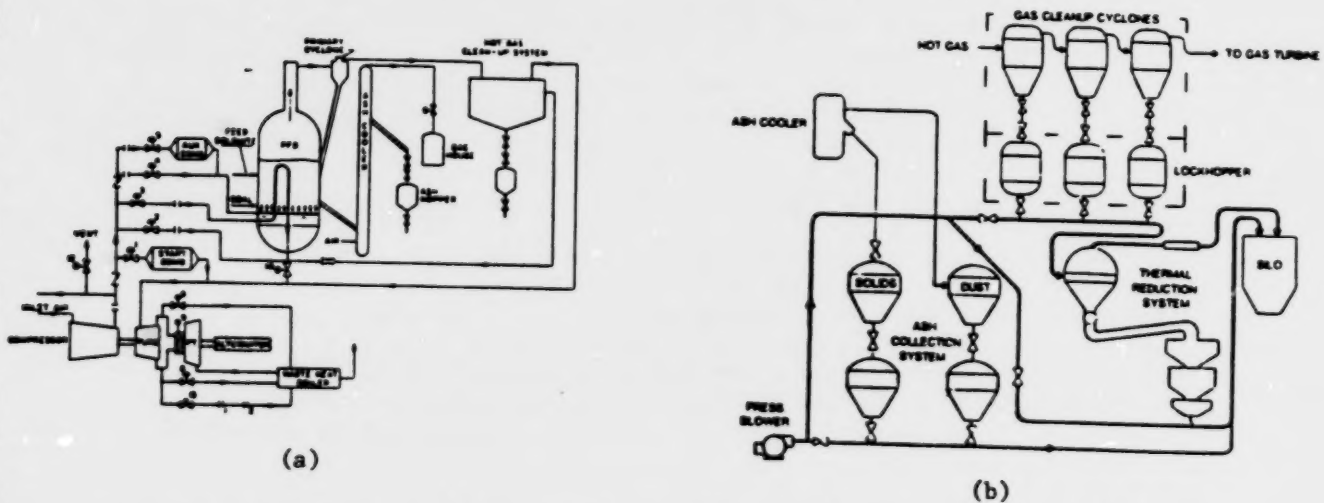


Fig. 2.6: Curtiss-Wright Schematic for Small and Pilot-Plant Units: (a) Process Schematic; (b) Hot Gas and Ash Handling Systems.

- Various alloy and coating materials for the gas turbine's stator vanes and rotor blades were tested. The 1000 h test results showed that protecting coating were needed to prevent corrosion/erosion attack. The most resistant coatings were platinum modified aluminide for the rotor blades and Fe-Cr-Al-Y vapor deposited overlay for the stator vanes.

- The heat exchanger tube materials most resistant to sulphidation/oxidation attack were the iron base type 310 stainless steel, the Fe-Cr-Al-Y cladding alloy and the cobalt-based alloy 188.

At the time of the visit, the test program on Acurex's ceramic felt bag for hot gas clean-up was completed. 99% removal of particulate was achieved.

13 MW_e Pilot Plant

Specific details are presented in Table 2 and in Figs. 2.5 and 2.6.

The design features are similar to that of the SGT rig. The combustor has a 3.8 m inside diameter and consists of a lower windbox section, a 4.94 m tall combustion section, and a 4.6 m freeboard section. There are 177 vertically oriented air-gas heat exchanger tubes in the combustion section.

At the time of the visit, the plant was under construction. The coal and dolomite handling and feeding systems, top section of combustor and off gas cleaning cyclones were already in place.

The test program on the pilot plant will include:

- Long term confirmation of materials and/or coatings for heat exchanger tubes and turbine blades and vanes;
- Determination of erosion/corrosion patterns associated with multi-stage turbine flow paths;
- Measurement of cyclone performance;
- Evaluation of system response to load changes and dynamic events.

AFB Coal Fired Boiler Plant

This plant was built in 1981 under the sponsorship of D.O.E. It burns 90,000 kg/day of anthracite refuse (HHV = 3126 BTU/lb) to produce 10,000 kg/h of saturated steam at 14 bar.

The AFB combustor is 3.05 m square. The steam is generated in in-bed vertical tubes and in a convective tube bundle above the freeboard.

Brief Conversation with Dr. S. Moskowitz, Director, Energy Systems

In general, Dr. Moskowitz was very optimistic about the future of PFBC. He hoped to be involved in the future development of B.C. Hydro's Hat Creek PFBC/CC power plant project. He welcomed our effort on PFBC work and offered to cooperate with us in some area of research and/or to provide technical assistance whenever needed.

2.2.6 Site Visit to Exxon Research Centre, Linden, New Jersey,
November 28, 1982

Background

Exxon started work on PFBC as early as 1974-75 under a contract from the U.S. Environmental Protection Agency. The entire facility is located in the Linden research complex of Exxon.

There are two separate plants, the "Miniplant", now abandoned, and a bench-scale unit on which some studies are continuing. Extensive studies have been concerned with sulphur absorption, sorbent regeneration, combustion efficiency, erosion and corrosion, hot gas cleaning and pollutant emissions.

Description of the Miniplant

This plant includes a Petrocarb coal-feed arrangement, sorbent feeding system, hot gas clean-up section, sorbent regenerator, scrubber and air compressor. A schematic diagram is shown in Fig. 2.7.

The combustor consists of a 61 cm ID steel shell. It is refractory-lined to an inside diameter of 33 cm. The 9.75 m high unit is fabricated in flanged sections to allow insertion and removal of the cooling coils. Various ports and taps are provided for maintaining pressure and temperature.

Heat is removed by cooling coils located in discrete vertical zones above the grid. Each coil has a surface area of 0.55 m^2 and consists of vertically-oriented loops constructed of 1/2" schedule 40 316 SS pipe.

Combustion-air is provided by a main air compressor having a capacity of 1400 scfm at 150 psig.

The combustor is preheated during start-up by a natural gas burner housed in the bottom plenum section of the combustor. Once the fluidized bed temperature reaches approximately 430°C , a liquid fuel system is used to heat the bed further to the coal ignition temperature. The liquid fuel, kerosene, is injected through a nozzle 15.2 cm above the combustor grid. The injector nozzle atomises the fuel to insure complete combustion. The liquid fuel is also activated during coal-feed problems to maintain the bed temperature above the coal ignition temperature.

Coal and sorbent are pneumatically injected into the combustor through a side-entry port 28 cm above the grid. The maximum solids feed rate is approximately 227 kg/h. The combustor is capable of operating at pressures up to 1000 kPa and temperatures to 1100°C , with superficial velocities up to 3 m/sec and expanded bed heights to 6.1 m. The expanded bed height can be controlled at any level above 2.3 m by continuous withdrawal of bed material.

Fig. 2.7: Exxon Fluidized Bed Combustion Miniplant

Solids are discharged by gravity through a refractory lined pipe into a "pulsed pot" from where they are pneumatically transported by controlled nitrogen pulses to a pressurized lock hopper. The distributor plate has 332 holes of 3/32" dia and four independent cooling water loops, each comprising 5 channels.

Combustion gases leaving the combustor go to a two-stage cyclone system. The first cyclone recirculates larger unburnt carbon particles back to the combustor to improve combustion efficiency. Particulates collected in the second cyclone are dropped into a lock hopper and disposed off on a batch basis. There was refractory deterioration in the second stage cyclone and it was therefore recast with more resistant CRUSCO-RS-17-EJ. The barrel was also made smaller to correspond to the smaller inlet and outlet pipes. This did not change the collection efficiency significantly.

Description of the Batch Combustor

The main batch combustor was constructed in four sections as shown in Fig. 2.8. Each section was a 10" diameter pipe lined with Grefco Litecast No. 7528 poured refractory to an inside diameter of 11.4 cm. The height of the vessel, above the fluidizing grid was about 4.9 m. Below the grid there was a 61 cm long burner section. The grid had 80 x 0.16 cm dia holes. It has water cooling channels. A propane burner, located in the preheating section, heated the bed to 505°C. At this point propane was added directly above the distributor. This raised the temperature of the bed to the desired level. Maximum operating temperature and pressure of the bed are 1000°C and 1000 kPa respectively.

The combustor had three vertical cooling coils made of 0.95 cm dia SS tubes. They extended from 27 to 141 cm above the fluidizing grid and each had a surface area of 0.06 m².

Sorbent was fed into the combustor through a port in the upper section. Solids could be removed through a port in the lower section or, alternatively, transferred directly to the adjacent batch regenerator through a 5 cm diameter pipe. Coal entered through a 'sonic' coal injection probe connected to the end of a 6.1 m x 0.58 cm dia coal injection tube. The inside diameter of the probe is 0.77 cm. The stream of coal was surrounded by seven sonic air jets to clear a path through the fluidized solids in the combustor. The air flow, amounting to 50% of the transport air, also helped cool the probe.

Gases leaving the combustor first passed through two cyclones. An off-gas cooler reduced the temperature of the off-gas to the desired level. The off-gas then entered a coil of 2.5 cm diameter stainless steel tube which was electrically heated during start-up to raise its temperature above the dew point. A 3.81 cm dia Aerotec cyclone, located downstream, was used to remove particulates during start-up of the combustor, when water vapor condensation in the first two cyclones caused them to operate at reduced efficiency.

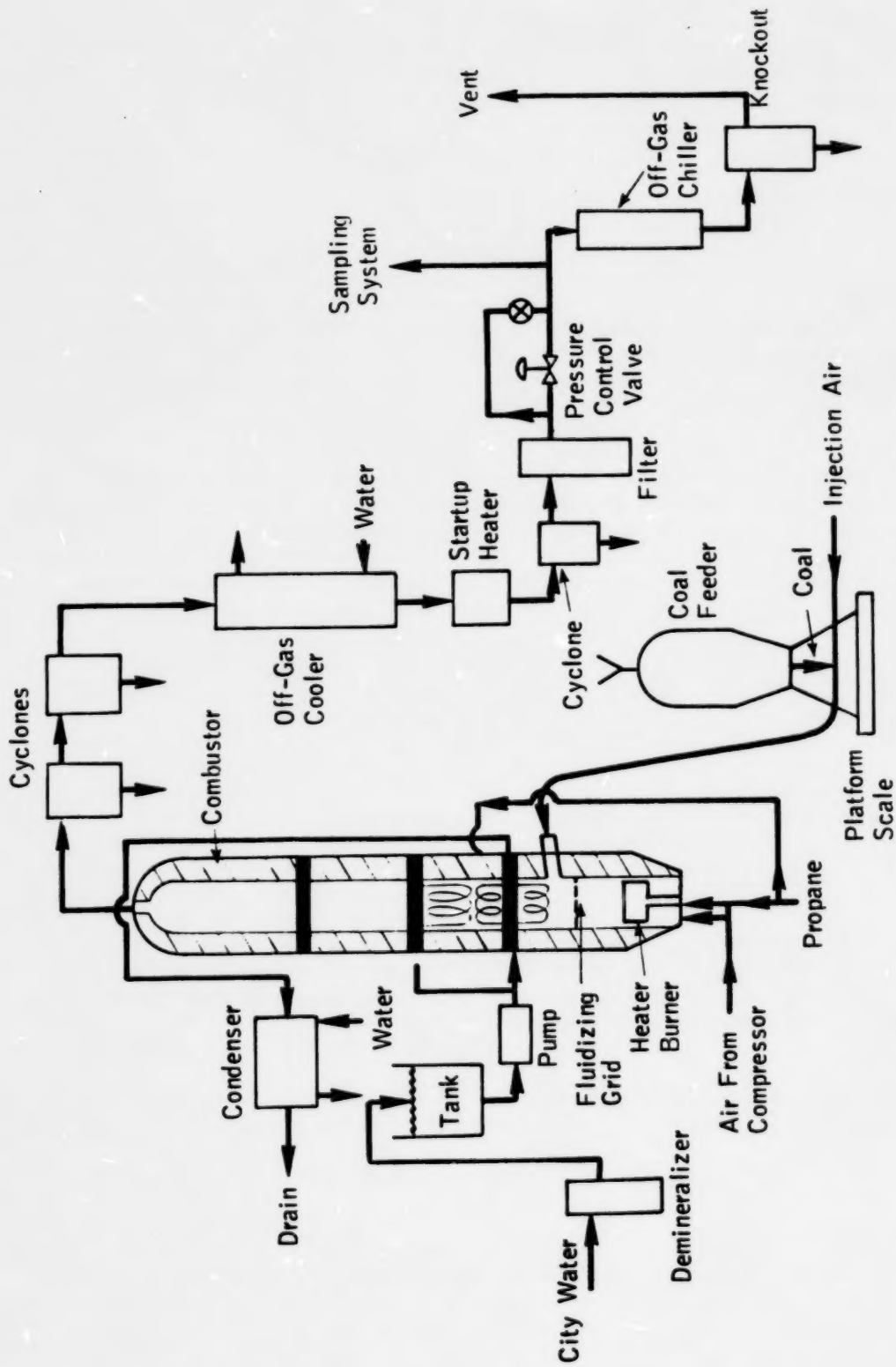


Fig. 2.8: BATCH FLUIDIZED BED COAL COMBUSTION UNIT (Exxon)

Disposal of the Miniplant

The original cost of the miniplant was over seven million dollars. DOE will take over the equipment and the components. The usual method of disposal involves enquiring if other DOE projects could use it. If not, it will be offered to universities. If none of the universities are interested, the equipment will be auctioned. The people to be contacted about the disposal are Ken Markle of DOE, Morgantown and Bruce Herschill of EPA, Research Triangle.

Perceptions of PFBC

Dr. Matulevicius felt that PFBC is not very competitive with conventional pf systems without scrubbers. Judging from the present pace of research on hot gas cleaning, DOE was said to feel that a hot gas clean-up system will be ready by 1991-92. Had the earlier emphasis on energy research continued, one would have expected commercialisation of PFBC by 1986. Presently GE is looking at a cladding compound, which has promise of being erosion and corrosion resistant. Some catalytic crackers use turbine blades made of carborundum which are suitable in a reducing environment, but do not work well in oxidising environments.

Turbo expanders can be used for temperatures less than 1200°F. Their use in PFBC is more to demonstrate the technology than to attain high efficiencies. Circulating PFBC may have some edge over lower velocity systems in the sense that recycled fines improve sulphur capture.

2.2.7 Site Visit to General Electric Company, Schenectady, NY Dec. 14, 1982

General Electric has been involved in PFBC technology development since the mid-1970's. The company has been involved mainly in the following three areas:

- conceptual studies and module design of PFBC combined cycle power plant.
- hot gas clean-up systems
- turbine material durability in the effluent from PFBC

All their work has been funded by the U.S. Department of Energy.

General Electric currently operates a 0.3 m diameter PFBC long-term material testing (LTMT) facility in Malta, NY. This rig was built at the cost of approximately \$1.0 million US, excluding the engineering, between 1977 and 1981. The rig has been used in research experiments to identify promising corrosion-resistant materials for use in PFBC demonstration/commercial plants, and to evaluate the effects of temperature and gas velocity on erosion/corrosion attack of gas turbine materials. More than 2000 hrs of test have now been carried out on this rig on a wide range of turbine materials.

The morning was spent with Mr. Thomas Bonds (manager of test operations) and Mr. Robin Brobst (material engineer) in Malta, visiting the LTMT facility and the afternoon in Schenectady with Dr. Russ McCarron, Manager of PFBC materials, and presently in charge of the LTMT program.

Long Term Material Test (LTMT) Facility

A schematic of the LTMT facility is shown in the Fig. 2.9 and the specific details are summarized in Table 2. The facility is located inside a large building on a four-story steel structural tower. There are separate rooms for air compressors, and control and analytical instrumentation. The facility consists of two coal/dolomite feed systems, a combustor, a three-stage cyclone cleanup system and two material test sections. There are sampling trains for both alkali vapor and particulates in the off-gas. Instrumentation for the system includes analyzers for O_2 , SO_2 , CO_2 and NO_x . The fluidized air is supplied by four 45 HP (100 cfm x 150 psi) Joy compressors operating in parallel.

The combustor design was adapted from the 0.3 m test rig at NCB/CURL. It is 0.3 m inside diameter and the shell is made of 0.6 m diameter carbon pipe and tee sections, and is built to operate at 10 bar and 955°C. The first, low velocity test section (LVTS) is a long RA-333-4" diameter pipe containing 180 pin specimens, while the second, high velocity test section (HVTS) contains four six-vane cascades.

Coal and dolomite, prescreened to -1.6 mm, are delivered in drums. They are premixed before being fed into a storage lockhopper. There are two identical feed systems. Each is made up of 2 lockhoppers, a rotary valve to meter the coal into the transport line and three load cells to measure the feed rate.

This facility is operating 24 hours/day, 5 days/week on a two-weeks on and one week off (for service and test specimen inspection) cycle. The program involves seven full-time personnel (2 engineers and 5 technicians).

On the day of the visit, the facility was in operation and ran without problems at 10 bar and 895°C and at a fluidizing velocity of 0.84 m/s. High sulfur coal was being burnt with a feed rate of ~ 50 kg/h and a Ca/S ratio of 2. The off-gases analysed after the cyclones contained 5% O_2 , 13% CO_2 and 500 ppm of SO_2 .

Some experimental results from this rig were presented at the recent 7th International Fluidized Bed Combustion Conference (172,173).

Conversation with Dr. McCarron, Manager of PFBC Material

(a) PFBC/CC Power Plant

GE's work on conceptual studies and module design started in 1976. A module design of a 679 MW_e steam-cooled PFBC/CC power plant was completed in 1979. The module, consisting of three identical PFBC units, was designed to operate to 10.5 bars and 954°C. The steam turbine was to generate about 75% of the plant's electrical output, with the remainder to be generated by expanding the cleaned hot flue gas through a gas turbine.

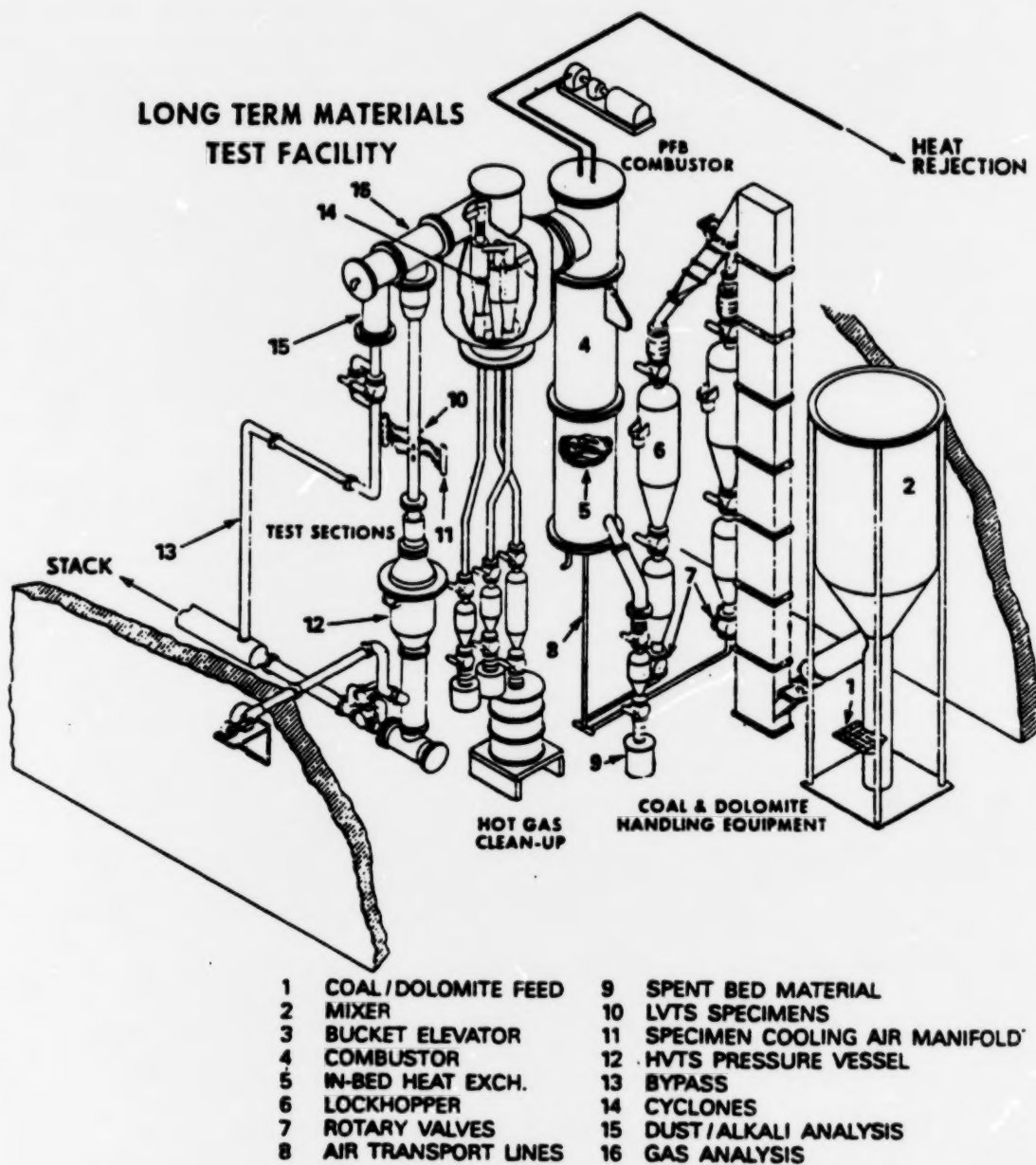


Fig. 2.9: Long Term Materials Test (LTMT) Facility
(General Electric)

No further development work was done in this area, since G.E. lost the D.O.E. contract to build a demonstration plant to Curtiss-Wright. However, Dr. McCarron felt that G.E.'s steam cooled system has the edge over the C-W air-cooled system because it is closer to the conventional cycle and therefore more acceptable to the utilities. They would like to build a demonstration plant if funding can be obtained in the future.

(b) LTMT Program

Work on the LTMT rig will be continued for the next two years to complete the 10,000 h turbine materials test period. The present 3-cyclone system removes up to 95% of the particulates in the hot gas. The particulate loading after the cyclones is 40-50 ppm with the average particle size of $2\mu\text{m}$. This loading is believed to be sufficient to prevent erosion attack on the gas turbine. However, Dr. McCarron thinks that, in commercial operation, with high flow rates and large cyclones, the removal efficiency of cyclones may be much lower. Advanced hot gas clean-up devices may be needed. Alkali vapor in the off-gases will present the most serious problem for the gas turbine. Present measurements on their LTMT unit indicate alkali levels of 2-10 ppm depending on types of coal and dolomite used. They have found that alkali vapor as low as 1 ppm in hot gas will attack the turbine material. Therefore, the alkali resistant coating is definitely needed to protect the turbine. At levels low enough to meet the pollution limit, SO_2 does not attack the turbine materials.

Prior to the LTMT program in Malta, G.E. was involved in tests on gas turbine materials in the facilities of Exxon at Linden, N.J., and of NCB/CURL at Leatherhead, England. G.E. provided the turbine test sections, specimens and material evaluations. Up to 1000 h of tests were conducted.

(c) Hot gas clean-up

G.E. has been involved in developing various advanced particulate and alkali removal devices. A G.E. electrocyclone is presently being tested at Curtiss-Wright's SGT rig.

2.2.8 Visit to IEA Grimethorpe, Yorkshire, U.K., Jan. 28, 1983

Talks were held with Mr. David McKendrick, Project Manager, Dr. Steven Wright, Irving Carls, K. Steinbauer and with several other members of the project team. All of the equipment was viewed during the visit.

This facility results from a joint project funded by the governments of the U.K., Germany and the U.S. under the auspices of the International Energy Agency. An agreement was signed in 1975 to share the costs of a PFBC facility. Construction of the facility was completed in 1980.

At the time of the visit, the facility had been shut down for just over a month for some modifications, in particular an extension of the heat transfer tube bundle closer to the distributor (from 0.9 m above the grid to 0.6 m above and replacement of worn tubes (see below)). The equipment was due to start up again very soon after the visit, by Feb. 1, 1983.

Many specific details of the facility appear in Table 2 below. In brief, the facility consists of a 2 m x 2 m square column with an overall height of 8 m hung inside a 4 m diameter x 14 m tall pressure vessel. A diagram appears in Fig. 2.10. The equipment is designed for pressures up to 15 bar, with an operating pressure range of 6-12 bar. A relatively broad range of operating conditions with bed heights up to 4.5 m and superficial air velocities from 0.8 to 3.7 m/s can be explored. Coal and dolomite are fed from up to 9 different feed points. There is provision for ash removal from the bed via a dry lock hopper system. Downstream, the gas is cleaned by 2 stages of cyclones, with a tertiary stage added to treat a slip stream of one-quarter of the off-gases passing to a newly installed static cascade to simulate a turbine. Air is supplied by a variable-speed stream turbine with the stream provided by the nearby existing power plant. The bed has water-cooled horizontal tubes. There is extensive instrumentation including an array of thermocouples, gas sampling for particulates and gaseous components, load cells to measure solids feed rates and automatic controls which can run the entire pilot plant.

Key findings to date are as follows: (a) The initial close-spaced tube bundle gave dead regions and large temperature gradients. Use of a larger tube spacing has eliminated this problem. However, there has been some serious erosion/corrosion on the tubes, not only on the lowest rows but throughout the bundle. This problem is causing some concern and has led to some cold model experimental work at Leatherhead. (b) There were some early problems also with solids feeding. Installation of rotary valves prior to the pneumatic feed lines has eliminated these problems. (c) There is no appreciable difference between feeding from 9 feed points and feeding with 5 in the current equipment. (d) Operation at 6 bar has led to similar findings to those in the 6 bar rig at Leatherhead; differences have been small and are explainable. It would appear that scale-up should not be unduly difficult. (e) Good combustion efficiencies, sulphur capture and NO_x levels have been achieved over about 1400 hours of operation under varying conditions using a UK coal and limestone. (f) Some corrosion data have been obtained using pins hung within the vessel.

In the near future, in addition to the cascade tests and extended heat transfer tube bundle, operation for 1400 h will be carried out with a higher sulphur American coal under five operating conditions and 700 h with each of two German coals (higher ash). It is also hoped that means can be found of preventing the erosion/corrosion problems noted above.

Altogether the equipment costs so far have been £18,000,000 (1980 pounds) with a further £4,500,000 spent on instrumentation and controls. Total costs including operating costs and equipment as well as coal (excluding only steam supplied by the existing power plant) to the end of Phase I are £60,000,000 (1980£). Phase I will be complete after the US and German coals have been tested as outlined above. Costs include site preparation, building costs, coal preparation facilities, nitrogen storage plus all personnel seconded to the project.

Cooperation between the three national groups is said to have been very good.

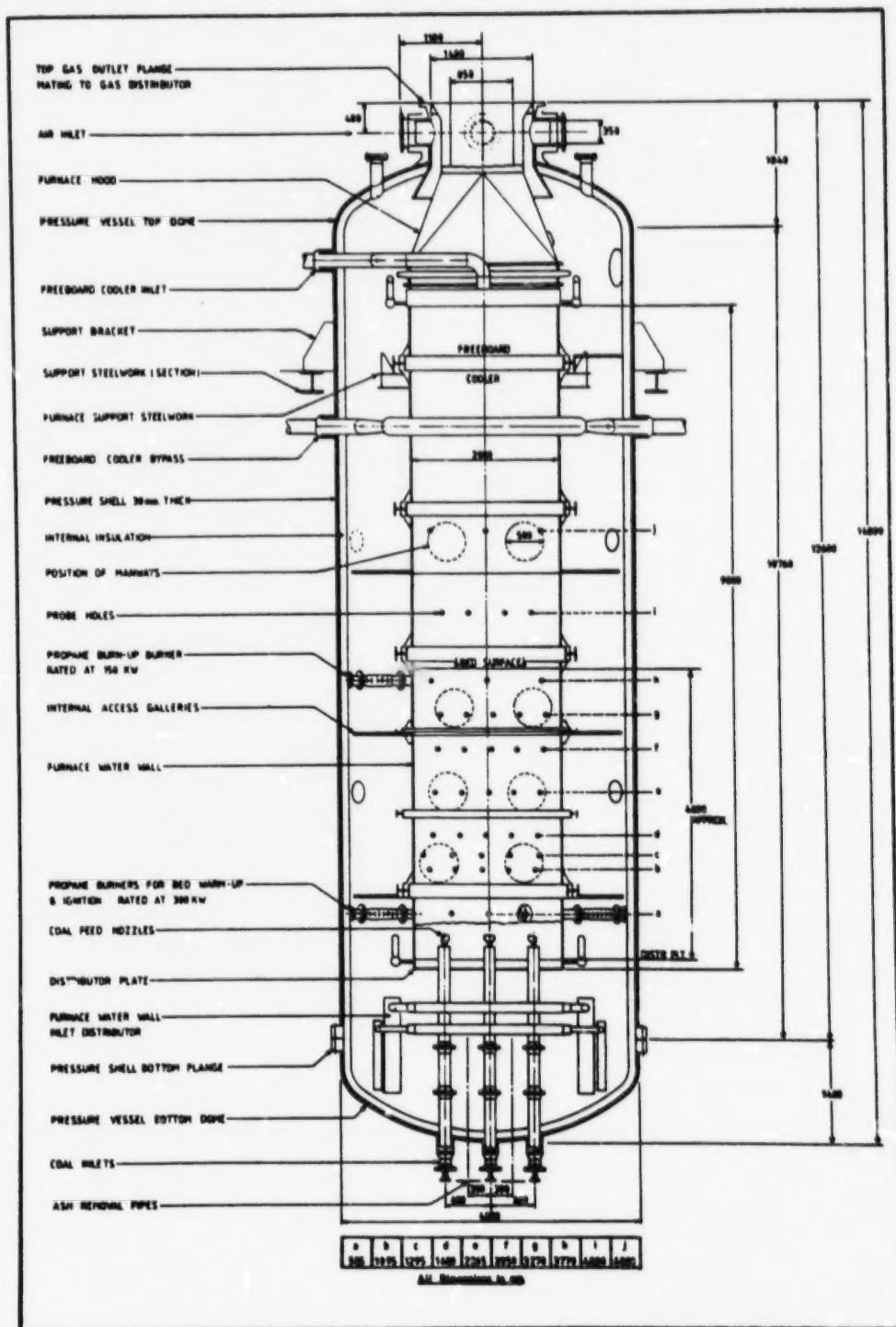


Fig. 2.10: IEA (Grimethorpe) PFBC Pressure Vessel and Column

There is concern now about Phase II, the turbine testing phase. The U.S. does not plan to participate beyond the end of the current phase (early 1984) because of budget restraint. The hoped-for next phase would see the PFBC unit become a feeder for testing turbine blades and materials. A further building would be constructed and tertiary cyclones would be installed for treatment of the entire off-gas stream. A small slip stream would still be directed to a static cascade. The turbine would be based on GEC's Bedford turbine, a flexible choice which would allow variable speeds and a variety of blades to be attached. Details are provided in a recently produced brochure.

It is hoped that new countries can be found to share the testing and in the cost of Phase II. Previous costs would be written off. It is clearly hoped that Canada will join this effort. More details of cost to join etc. should be available shortly.

The overall perspective of the IEA group regarding the future of PFBC is rather cautious. In England, the CEEB appears to be primarily interested in nuclear power, while there is unused coal-burning power generation capacity and little or no growth in overall demand. Hence short term prospects are bleak. In the longer term, the prospects appear to be brighter; they have no doubt that coal can be burned in pressurized beds efficiently, with the linked problems of hot gas cleanup and turbine longevity the last major problems to be solved.

2.2.9 Site Visit to NASA Lewis Research Center, Cleveland, Oct. 29, 1982

A 200 KW(t) pressurized, fluidized bed combustor and research test facility were designed, constructed and operated by the NASA Lewis Research Center. The facility was established as part of a NASA funded project to assess and evaluate the effect of PFB hot-gas effluent on aircraft turbine materials that may have applications in stationary power plant turbogenerators.

The facility which cost approximately \$1M in 1976 was intended for research and development work and was designed to operate over a wide range of conditions. Tests were carried out over a two-year period on such aspects as:

- a) type and rate of consumption of coal
- b) solid sorbent material
- c) ratio of coal feed to sorbent feed
- d) combustion air flow
- e) depth of the fluidized bed
- f) bed temperature
- g) bed pressure
- h) type of test unit exposed to combustion exhaust gases.

NASA has now terminated this project. The facility has been deactivated and parts of the system are being stripped off. The data processing unit, which was an extensive system, is being used for other projects. The gas analysis package is also being used on another project. Most of the other control interfaces have been discarded. The hardware is slowly being dismantled. Some sophisticated hardware remains at the site. There is some chance that parts of the equipment could be purchased.

Details of Facility

Key details of the experimental facility are summarized in Table 2. A diagram showing the experimental set-up appears as Figure 2.11.

Experimental Findings

The work performed at the NASA centre indicates that there will be severe erosion of turbine components unless the gas is carefully cleaned. Their experience suggests $10\mu\text{m}$ to be the largest particle that can be tolerated by gas turbines.

Initial experiments were carried out on erosion of fixed wedges by dirty gas coming directly from the combustor. This resulted in catastrophic erosion of the blades, even after only a few hours of exposure. A large number of turbine materials were used including nickel-based IN-738, IN-100, IN-792 and cobalt based materials. All of these showed signs of erosion and hot corrosion.

A gas turbine was also connected downstream from the unit. A 400 hour run was carried out with cyclones in position. Erosion and corrosion were beyond acceptable levels.

Based on this experience, the NASA representatives suggested that vapour-deposition of nickel-chrome-aluminium or iron-chrome-aluminium coatings may be required. Alternatively, the development of ceramic turbine blades combining the ability to withstand very high temperatures with resistance to corrosion and erosion may provide the ultimate answer. However, these materials are brittle and extremely sensitive to the manufacturing process. While automotive gas turbine rotors may be produced within 2-3 years, it will take longer to produce large ceramic gas turbines for turbogenerators.

2.2.10 Site Visit to New York State University, October 22, 1982

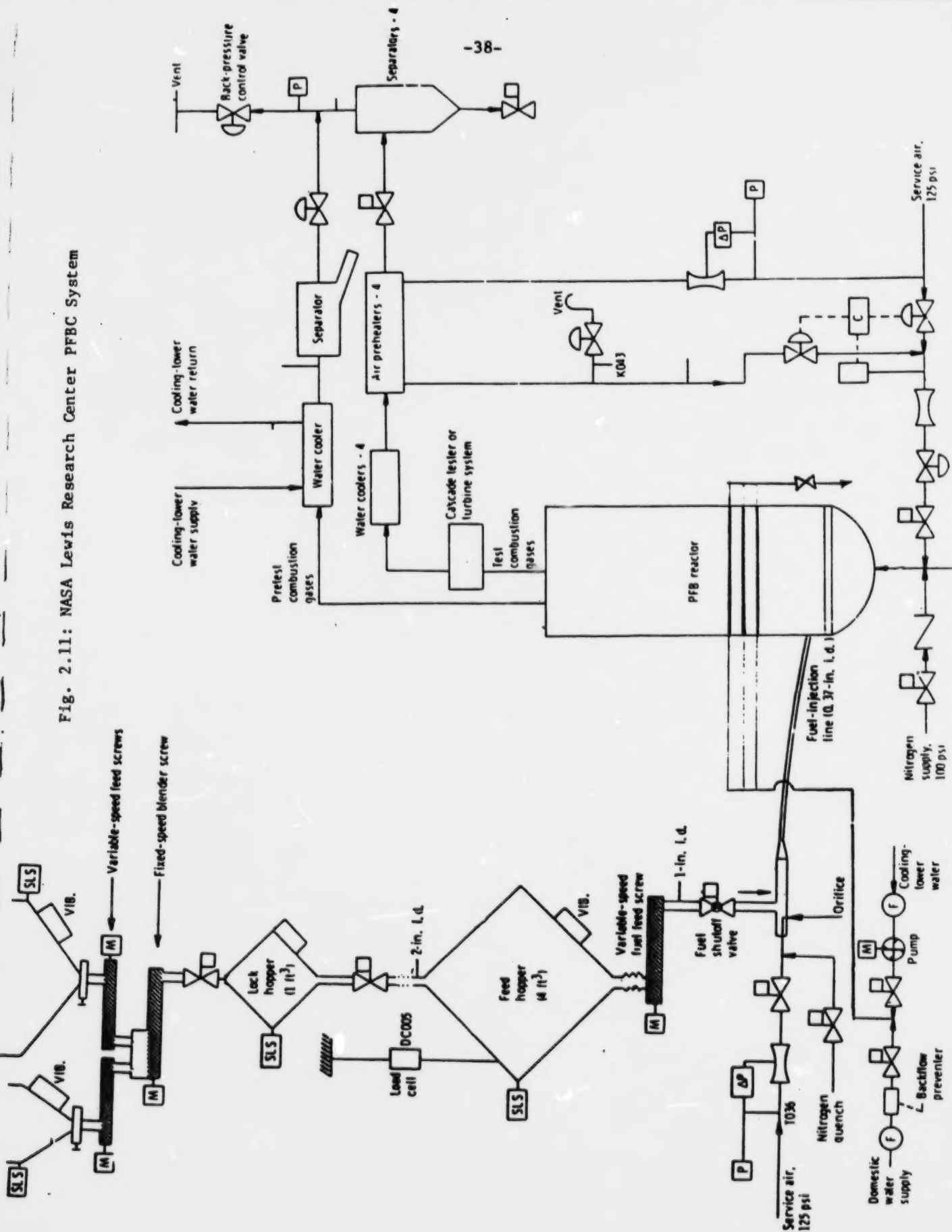
A programme was initiated at the New York University Antonio Ferri Laboratories in February 1976 to investigate the inter-relationships between temperature distribution, fluid flow and heat exchanger design on the performance of PFBC. Initially a pilot gas-fired 12" diameter PFB was built. It operated in the range of 1-10 atm pressure and at a maximum temperature of 800°F. This bed was heated by an externally fired gas burner.

Research at NYU on this unit was directed to understanding the mechanics within the bed in order to maximize heat transfer. Research has been concluded in the following areas:

- a) Gas velocity profiles at the distributor plate
- b) Heat exchanger design
- c) Effect of pressure on heat transfer
- d) Effect of deep beds on fluidization
- e) Effect of finned tubing on heat transfer
- f) Effect of heat exchanger solidity on heat transfer

The original unit has now been decommissioned and replaced by a newly built PFBC with a 30" internal diameter. Most of the work has been funded by D.O.E.

Fig. 2.11: NASA Lewis Research Center PFBC System



Present Status

The large PFBC, which is designed to operate up to 10 atm pressure, was undergoing a shakedown test at the time of the visit. Coal had been fired twice in this unit with a maximum continuous run of 4 hours. On the day of the visit, the unit was started up at 6:30 a.m. and was in operation until 11 a.m. The Lock-hopper control system caused so much problem that the unit had to be shut down. Plugging of pressure taps was thought to be the cause of failure of the control system.

Future Plans

Planned studies include:

- (i) Study of combustion and sorbent utilisation characteristics for lignites.
- (ii) Further studies on fluid mechanics in this larger bed.

This laboratory plans to study advanced concepts of PFBC in a specially-designed PFBC. It will be a two-stage combustor with straight hole distributor in the top bed. The lower bed will be of smaller diameter than the upper. Large chunks (1-2") of coal will burn here under high velocity and high excess air. The top bed will burn fine coals under a slightly reducing environment. There is an expanded section on top of this to help reduce carry-over. Admission of tertiary air at this stage will complete the combustion and hence increase the gas temperature.

Perceptions of PFBC Technology

Dr. Zakkay believes that PFBC will be commercialised within the next 5 years. He feels that gas cleaning is the most important issue for development of PFBC. Development of turbine materials is a parallel issue. Some progress in both areas is essential before the commercial breakthrough.

A reasonable amount of design information on heat transfer and combustion is available. Scale-up of PFBC as a whole must await demonstration of the Tidd plant. Dr. Zakkay further believes that vertical heat exchanger tubes will be superior to horizontal ones because they reduce the angle of attack of particles causing erosion. Research efforts in PFBC should be directed to hot gas clean-up and solid feeding into the bed.

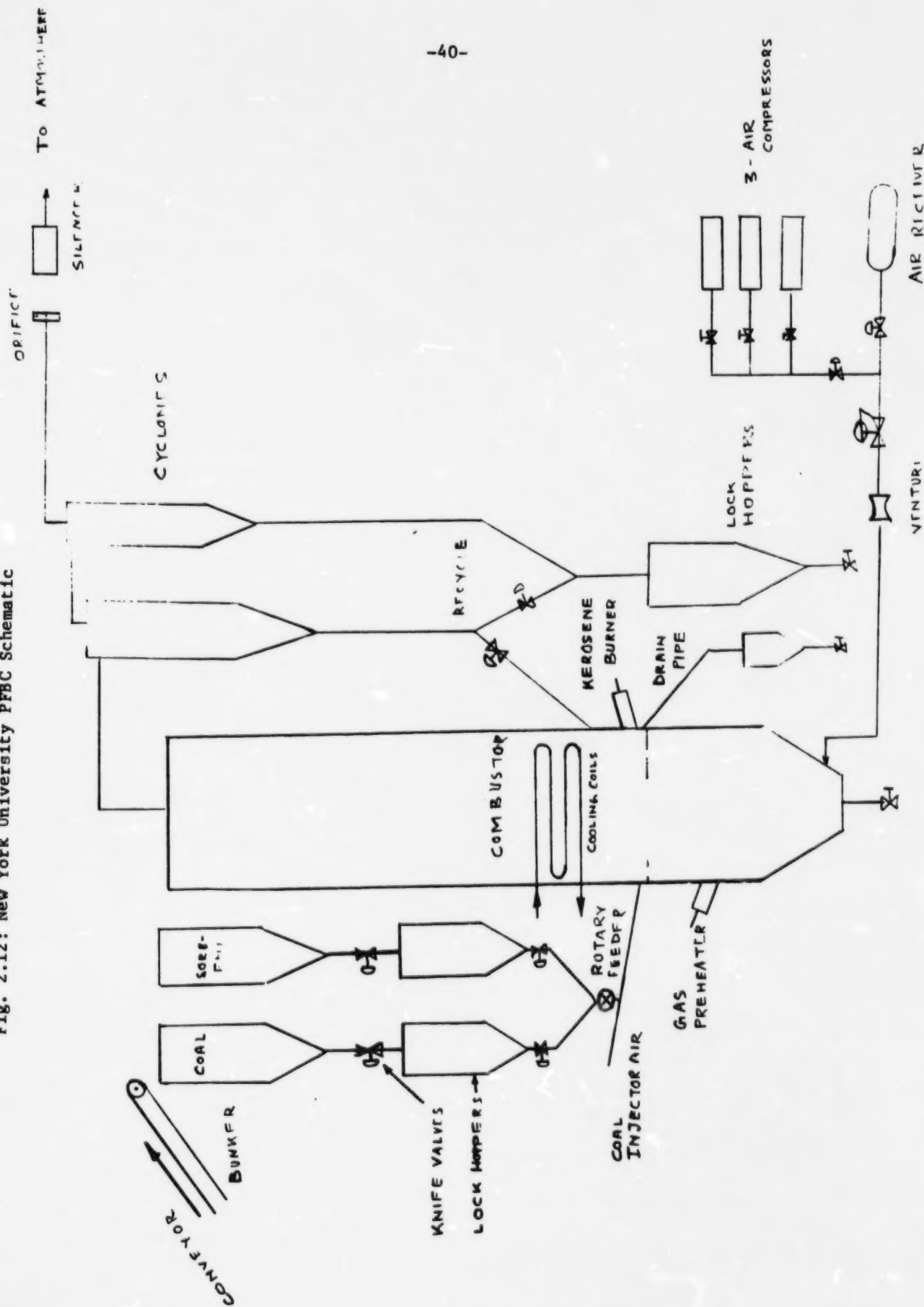
Description of Facility

A schematic of the facility is shown in Fig. 2.12. Some components are as follows:

(a) Solids feeding

Coal, crushed to 6 mm, is delivered in drums to a bunker. There are two legs of the bunker each having its own remote-controlled knife-edge valve connected to lock-hoppers. Each lock-hopper has two indicators to indicate the level of coal. A pneumatic control system closes the top valve and pressurises it as soon as the hopper is full. There are two

Fig. 2.12: New York University PFBC Schematic



more knife-edge valves at the outlet of the hoppers. A rotary feeder meters the coal into the pneumatic transport line. Coal is pneumatically injected into the bed at an angle of 30° to the horizontal and 12' above the distributor.

Dolomite has a similar system of feeding. There is only one coal feed point in the 30" diameter bed. The feed pipe is a SS 2-1/2" tube designed to carry 2000 lb/h coal at an air velocity of 30 ft/s.

(b) Distributor

The distributor is comprised of 2 plates. Nozzles are tapered at the top. The space between the plates is cooled by air and water. The fraction of open space in the distributor is 2%.

(c) Column

The column is a 244 inch long shell of 48" OD and 0.4" thickness. The inside is protected by layers of Altex 85B Firebrick and GR 2300 insulating bricks. The column is divided into 3 sections, bolted together by flanges. A large number of sampling points has been provided. One sight port is provided, about 12" above the distributor, to view the bed.

Thermocouples are located on 6 levels with 4 on each level. Each is fitted inside another 1/4" sheath with the help of a swedge lock fitting. Pressure taps have created frequent problems. As a result of the high pressure, solids flow into the pipes and clog them. Installation of special filters in front of the pressure taps is planned.

(d) Cooling coils

There are 3 bundles of horizontal cooling coils in the fluidized bed. Each bundle has 4 rows of unfired tube in a staggered pitch of 3.75" horizontal pitch and 2" vertical pitch. The tube diameter is 1.66". About 23 gallons of water per minute pass through each coil at 50 psig. There is no pump; water flows from a pressurized tank.

(e) Air supply system

Initially a large compressed air storage vessel was used for supply of air. Now three large 11,000 cfm x 120 psig compressors have been rented. The air is passed through a valve, venturi nozzle and a series of control systems. Air enters the refractory-lined air plenum through a manifold.

(f) Start-up

There are two start-up propane burners each having a firing capacity of 500 cfm. The starting bed depth is only 8". Initial air supply is from a blower. This heats up the bed to 1000°F. Then one 11x10⁶ BTU/h kerosene burner is started and blows directly above a slightly fluidized bed. Coal is started when the bed-temperature reaches 1400°F. The air supply is gradually switched over from blower to the compressor. Kerosene is switched off when the bed-temperature reaches 1600°F. Then the bed depth is built up slowly. About an hour is required to stabilize the system.

(g) Gas clean-up system

There are two refractory lined cyclones in series. The primary one is 18" ID while the secondary one has a diameter of 12" ID. A cooling jacket is provided on the leg of the cyclones. There is one lock-hopper with two knife-edge valves. The dusts can either be recycled or collected at the bottom. A conveyor carries out all the ash for disposal. The secondary cyclone is connected to a 12" pipe. The gas passes through a nozzle to maintain the required furnace pressure of 7 atm. There is one silencer on the exit flue gas line.

2.2.11 Site Visit to Stal-Laval, Sweden, Feb. 3 and 4, 1983

Stal-Laval Turbin, a subsidiary of the Swedish company ASEA, has been active in the PFBC field since about 1970. It initially cooperated closely with the British Babcock and Wilcox company, and has joined forces with American Electric Power since 1976 and Deutsche Babcock since 1980. Stal-Laval has been chiefly responsible for the gas turbine, hot gas clean-up and auxiliaries in the joint effort.

(A) Atmospheric Fluidized Bed Combustion Boiler (Multi Bed Combustion)

The early morning of Feb. 3 was spent with Lars-Olof Ingerson who is in charge of marketing a new AFBC boiler in the 10-50 MW range for district heating and industrial use. A prototype has been built and tested near Linköping and I was shown this unit. Called a "Multi Bed Combustor", this unit has four separate compartments in series. The bottom stage serves as the principal combustor, with afterburning occurring in the second stage. The top two stages are essentially for heat recovery. Horizontal heat transfer tubes are present in each of the stages. A means of external solids circulation is provided between the stages, but the details are proprietary. Start-up is with both electricity and oil firing. Load cells are used to monitor the solids feed rate. Discharge of ash is through the base plate, with provision for heat recovery from the hot solids. Solids feeding is by pneumatic conveying through the base plate.

(B) Pressurized Fluid Bed Combustion Work, Finspong

Host for the afternoon was Sven Jansson. Unfortunately, it was not possible to visit the new installation at Malmö, since they are still having some early problems with solids feeding and withdrawal. However, Jansson and his colleagues were helpful and generally informative, although some details are of a proprietary nature. The visitor (JRG) also gave a seminar while there to a small group on our own work.

Stal-Laval has been involved in PFBC for about twelve years (see (C) below). They manufacture large turbines for power generation. Their GT120, the workhorse since 1958, would, in their opinion, be ideal for PFBC operations providing some minor modifications are made. In recent years they have joined forces with American Electric Power and Deutsche-Babcock in an effort to prove the viability of the technique. Tests have been done in house on erosion and corrosion of tubes and on emissions and sulphation. Tests have also been carried out at CURL, and Stal-Laval is a co-sponsor of the 12 inch square unit there. In addition, a tapered unit

of approximately 1.0 x 2.0 m cross-section has recently been built at Malmo to test the operating conditions and component reliability of the system which may be built as a demonstration unit at Tidd, U.S. A diagram showing the Malmo facility is shown in Fig. 2.13, and many details are given in Table 2 below.

Tapering is used because cold model studies have shown favourable solids mixing right to the bottom of tapered beds. The Malmo unit employs horizontal tubes in a water cooled column immersed in an outer pressure shell. Feeding and discharge are via lock-hoppers and pneumatic conveying lines. A cascade and simulated rotating blades will be used to test turbine materials. While the Malmo installation has had problems since its start-up in late 1982, the problems are regarded as temporary. The range of conditions to be investigated is relatively narrow. Upon completion of the tests for Tidd, Stal-Laval would be willing in principle to run tests for others.

In parallel with the experimental work in progress at Malmo and at CURL, extensive work is in progress in the current year to prepare detailed cost estimates for a 1300 MW PFBC electric power plant. The Stal-Laval group are optimistic that the approximate 10% cost advantage of PFBC over conventional generation methods will be maintained, although they admit that the accuracy of previous estimates is no better than $\pm 10\%$. The Stal-Laval GT 120 high pressure ratio turbine is believed to be capable of operating on the gas turbine cycle side with minor modifications. While they have looked at the possibility of using a turbo-expander, their calculations indicates that this will have an efficiency about 1.5% lower than the combined cycle operation. While they believe firmly that PFBC will prove to be safe and reliable with a high availability, there are no absolute assurances of this at this time.

Work they would like to see done in universities would include:

- (a) studies of solids mixing and motion in tapered beds and through tube banks;
- (b) bubble growth and behaviour in tube banks;
- (c) forces on tubes at elevated pressures.

(C) Conversation with Henrik Harboe, Vice-President of ASEA and Stal-Laval, February 4, 1983.

Mr. Harboe has been closely associated with pressurized fluidized bed combustion at Stal-Laval since 1969. He has been something of a crusader for PFBC, especially for combined heat and power applications. He was apparently instrumental in keeping the CURL labs going at one critical stage. Despite the setbacks and delays, he still seems to be committed to PFBC, and the long involvement of Stal-Laval, without any orders for large-scale plants, bears witness to this. He described in some detail the various negotiations which have gone on with Deutsche Babcock and more recently American Electric Power.

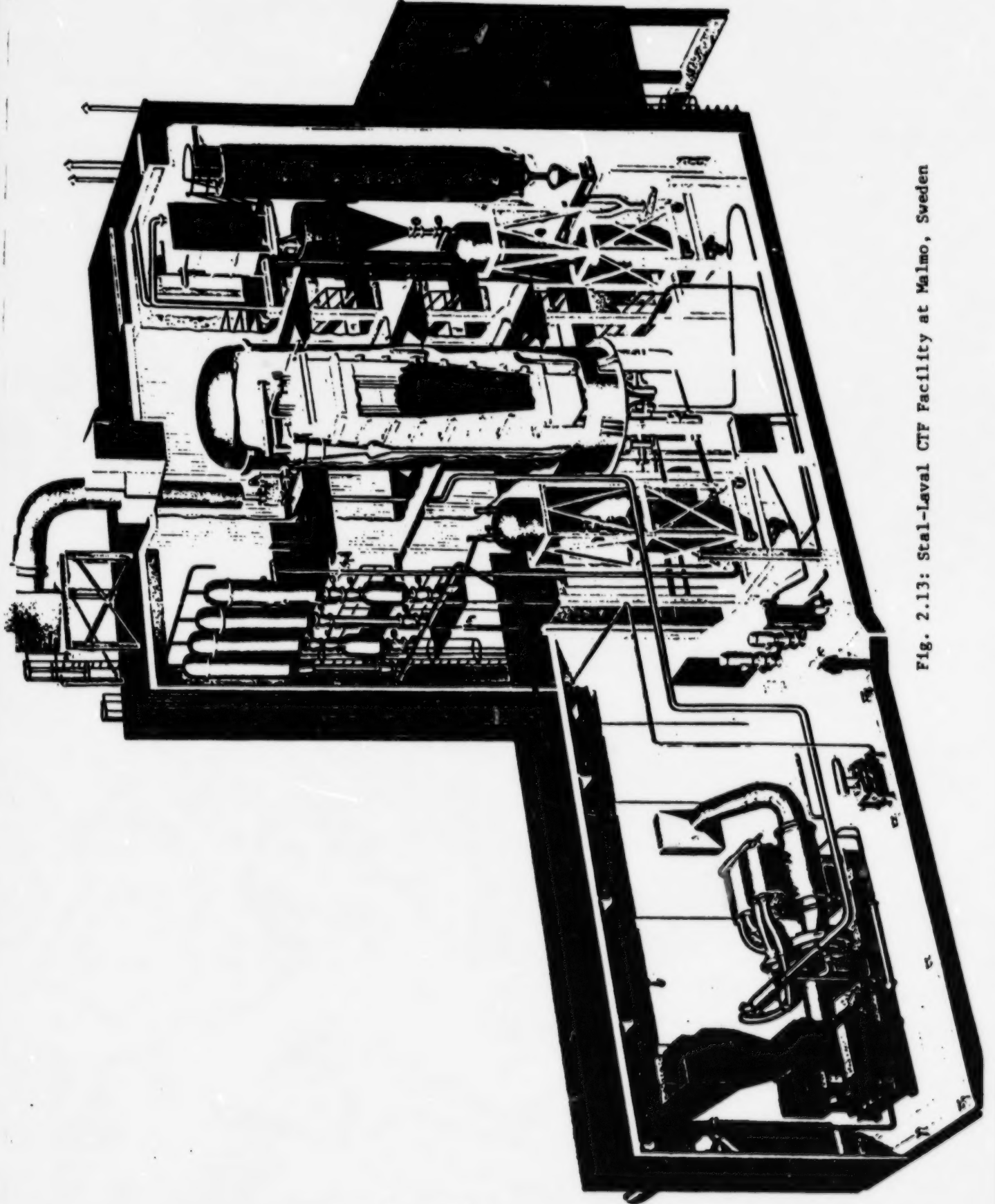


Fig. 2.13: Stal-Laval CTF Facility at Malmo, Sweden

Mr. Harboe sees the most serious problems in large-scale PFBC to be solids feeding and withdrawal, tube erosion and turbine longevity. However, he thinks all of these components can be made to work, and in fact could have been made to work eight years ago or so. He sees Grimethorpe as expensive and not very helpful.

Stal-Laval considered at one time turbo-expanders. However, they do not believe them to be very attractive because efficiencies are no better than for conventional cycles. He still feels that the gasification route to electric power is not as attractive as PFBC due to problems in gas cleaning, lack of attractiveness for district heating, and materials handling. He believes that it will be some years before ceramic blades or cooled blades are developed to allow high enough temperatures to make the efficiencies significantly higher.

Mr. Harboe still believe that Stal-Laval's GT 120 turbine is the best turbine around for the specific purpose of PFBC. He feels that there is a very good chance that the Tidd plant will not go ahead. However, he is quite optimistic that a full-scale plant will go ahead soon, with Sweden, Germany and Denmark being the most likely places. These three countries may well act together.

Stal-Laval would welcome Canadian tests at Malmo. He asked in particular about Canadian district heating practices as he feels that combined heat and power generation could be very attractive for PFBC schemes. He says that work is well advanced in Europe in developing a novel "coal pump" which would greatly help the coal feeding problem. He is not very favourable about circulating beds, atmospheric or pressurized, although he admits that he is not very knowledgeable. The key disadvantage he sees stems from the need to extract sufficient heat. If a separate bed is used (e.g. as by Lurgi or Batelle) the system becomes rather complex. Mr. Harboe emphasized that much of the PFBC market in the intermediate term should consist of retrofitting older electrical generating capacity. Benefits will include replacement of oil by coal, somewhat increased overall capacity, improved efficiencies and, possibly, improved use of waste heat.

2.2.12 Summary of Experimental Facilities

To allow comparison between the various experimental facilities of size greater than about 0.2 m in diameter, we have prepared Table 2 summarizing the principal features of the facilities visited. It is clear from the table that the units operated have varied considerably in their principal dimensions and geometry and in the approaches adopted to solve some of the key problems. The twelve facilities also show a broad range in some of the key operating variables such as pressure and excess air. While three of the units are now inactive, the others are still in active use or, in one case, under construction.

TABLE 2 - DETAILS OF MAJOR PFBC EXPERIMENTAL FACILITIES VISITED

Organisation	ARGONNE NATIONAL LAB	CURL	CURL	CURL
Location	Argonne, Ill., U.S.A.	Leatherhead, Surrey, UK	Leatherhead, Surrey, UK	Leatherhead, Surrey, UK
Operating Period	1974 - present	1969 - 1981	1975 - present	1981 - present
Chamber Inside Dimensions (m)	0.15 dia	0.6x0.9(or 1.2)x2.7 high	0.30 dia x 3.7 high	0.3x0.3x5
Chamber Cross-Sect. Area (m ²)	0.018	0.56 - 0.84	0.073	0.09
Pressure Range (bar)	3-12	3-6	1-6	6-20
Temperature Range (°C)	775-982	700-950	750-930	760-950
Superficial Velocity (m/s)	0.6 - 1.5	0.6 - 2.5	1-5	0.9-1.5
Excess Air (%)	15-75	15-300	20-150	20-100
Bed Depth (m)	1 m static	1.2-2.5	1-1.5	2-2.7
Coal Feed Rate (kg/h)	20	typically 800	typically 23	NA
Sorbent Feed Rate (kg/h)	NA	Ca:S from 0 to 3	NA	NA
Thermal Rating (MW _{th})	0.15	4.5	0.25	1.0
Start-up Method	Electrical	Propane	Propane	Propane
Shell Dimensions (m)	0.46 dia x 2.6 high	1.8 dia x 5	0.61 dia x 3.7 high	0.76 dia x 5 high
Refractory Type	Cast KI-mix and verillite	Cast	Cast	Cast
Distributor	Bubble cap, downward - inclined jets; 8 caps with 6 x 1 mm dia holes per cap	Bubble caps on 76 mm x 76 mm pitch	Bubble caps	16 Capped Spargers, 10 holes per sparger
Solids Feeding System	1 feed point from lock hopper and pneumatic feed system via 13 mm pipe (9-15 m/s conveying velocity) and air-lock rotary feeder	Lock hopper, rotary valves, pneumatic conveying through 2 nozzles; dolomite through similar smaller system	Pneumatic co-feeding of coal and sorbent via 19 mm pipe; screw screw feeding tests and slurry feeding. Feed vessels on weigh scales.	1 feed point from side, 0.16m above grid, pneumatic co-feeding of coal & sorbent; rotary valve between lock-hopper and feed line; conveying at 10-15 m/s thru 19 mm pipe
Coal top size (mm)	2.4	1.6-3.2		4.0
Sorbent top size (mm)	2.4	NA		3.2
Solids Discharge System	Side outlet overflow pipes; and cyclone discharge into lock hoppers	Bottom outlet to pressurized vessel	Side outlet overflow pipe.	Continuous vertical downflow via butterfly and ball valves into lock hopper which is discharged periodically; cyclone catch is discharged separately.
In-Bed Heat Exchangers	5 Vertical 9.5 mm dia. tube loops, SS-316	Horizontal tubes, 25 & 38 mm dia., and vertical tubes, 150 mm dia. Approx. 15% of bed occupied	Coil in lowest portion	25 mm dia. horizontal tubes; max 119 tubes in 2.1 m height
Hot Gas Clean-up Devices	2 refractory lined cyclones in series, dia. 100 mm and 51 mm, supplemented by stainless steel screen filter and granular bed filter	Tubes in freeboard to reduce splashing; up to 3 cyclones in series	203 mm cyclone plus venturi scrubber	One cyclone + venturi scrubber
Downstream Devices	None	Cascades in some tests	None	Cascades to be added.
Major Investigations	Effect of temperature, air velocity and sorbent feed on sulphur retention, NO _x emissions, combustion efficiency, particle emissions; study of regeneration of sulphated dolomite; hot gas clean-up by granular bed filters and TAM-JET cyclones.	Corrosion & erosion; particulate, alkali, SO _x , & NO _x emissions; bed performance; various coals; heat transfer; sulphation; dust sampling; cyclone performance; cascade tests; tapered bed	Combustion of wide variety of coals and coal-water mixtures; combustion efficiency, heat transfer, entrainment, sulphur capture.	Operations at higher pressures than previously; temperature gradients; heat transfer; combustion efficiency; sulphur retention; SO _x and NO _x levels.
Current Status of Work	Characterisations and regeneration of sorbents.	Inactive for past two years but still available.	Still in use; currently used for tests on coal water slurries and run-of-mine coals.	Booked for tests on various coals (incl. Mat Creek) as well as work on erosion and cascades.

TABLE 2 - DETAILS OF MAJOR PFBC EXPERIMENTAL FACILITIES VISITED (Continued)

Organization	CURTISS-WRIGHT	CURTISS-WRIGHT	EXXON	GENERAL ELECTRIC
Location	Wood-Ridge, N.J., U.S.A.	Wood-Ridge, N.J., U.S.A.	Linden, N.J., U.S.A.	Malta, N.Y., U.S.A.
Operating Period	1977 - present	Under construction, operational end of 1983	1975-1980	1982 - present
Chamber Inside Dimensions (m)	0.93 dia x 9.6 high	3.8 m dia	0.32m dia x 9.8 high	0.305 dia
Chamber Cross-Sect. Area (m ²)	0.68	11.3	0.80	0.073
Pressure Range (bar)	5.1 - 6.8	up to 7.1	1 - 10	up to 10 bar
Temperature Range (°C)	up to 900	up to 900	up to 982	870 - 950
Superficial Velocity (m/s)	0.83	0.83	up to 3.0	0.77 - 0.93
Excess Air (X)	30	30	11 - 19	10 - 30
Bed Depth (m)	4.9	4.9	2.3 - 6.1	=1.6
Coal Feed Rate (kg/h)	266	4655	227	=65
Sorbent Feed Rate (kg/h)	114	Ca:S = 1.5	180	Ca:S = 2-2.3
Thermal Rating (MW _{th})	2.3	40	0.6	0.45
Start-up Method	External combustor fired with gas or liquid fuel	External gas or liquid fuel	Hot gas below bed + kerosene	Propane
Shell Dimensions (m)	1.76 dia x 23 total height	4.63 dia	0.61 dia x 9.8	0.61 dia x 4.3 high
Refractory Type	Castable alumina type 0.305m thick	0.305m thick lining; Free-board - castable alumina type; Bed - shell side castable alumina, gas side high purity & high density alumina	Bussco RS-17-E & Suprex-2000 brick	Castable alumina type
Distributor	Tuyeres in a square pitch pattern	Tuyeres in a square pitch pattern	Water-cooled perforated plate, 332 hole @ 2.4 mm dia.	16 capped 0.95 cm dia SS 310 pipes which discharge air horizontally 7.6 cm above the plate surface. 1 feed point from bottom; pneumatic co-feeding of coal & sorbent through a 25 mm dia pipe; coal & sorbent are discharged horizontally 0.17m above air distributor. Rotary valve between lock-hopper & feed line
Solids Feeding System	1-feed gun for coal & 1-feed gun for dolomite, both horizontally from side; lock hopper followed by pneumatic transport via 12.7 mm pipe.	Coal-8 feed guns horizontally from side & 4 vertically from bottom; Dolomite-2 feed guns horizontally from side. Lock hopper followed by pneumatic transport via 12.7 mm pipes	Petro-carb feed system and load cell feeding through 13 mm pipe 0.28 m above distributor with annular injection of air	
Coal top size (mm)	3.2 mm (<0.5% surf. moisture)	3.2mm (<0.5% surf. moisture)	3.4	=1.6 mm
Sorbent top size (mm)	3.2 mm	3.2 mm	2.4	=1.6 mm
Solids Discharge System	Bed ash removed continuously from side outlet just above distributor plate & pneumatically transported through a fluidized bed cooler into lock hopper; Cyclone ash falls continuously into lockhopper.	Bed ash removed continuously from side outlet just above the distributor plate & pneumatically transported through a fluidized bed cooler to lock hopper. Cyclone ash falls continuously into lockhopper.	Bed solids discharged intermittently via dual valves; solids from first cyclone reinjected using nitrogen pulse; other cyclone solids captured in lock hopper.	Discharge periodically through side outlet into lock hopper. Cyclone catches discharge separately.
In-Bed Heat Exchangers	9 vertical air-cooled tubes, 24 cm spacing; re-entry type design; outer tubes 102 mm x 4.9 m high SS pipe with interior fins; inner tubes are 51 mm dia. and insulated.	Vertical air-cooled tubes, 24 cm spacing; re-entry type design; outer tubes 127 mm dia x 4.9 m high SS pipe with interior fins; inner tubes 31 mm dia. and insulated.	Both horizontal & vertical coils, 19 mm dia, 316 and 3.161 SS; 4 vertical coils, 0.35 m ² /coil.	Water-cooled helical coils (<0.2 m O.D.) located between 0.6 m above grid bed surface. Coil made of 19 mm dia SS 310 pipe and has active length of 8.6 m.
Hot Gas Clean-up Devices	1977-1980: 4 stages of cyclones, one with recycle. From 1981: 2nd stage cyclone replaced by electrostatic precipitator, electrocyclone or ceramic felt bag.	4 stages of cyclones, one with recycle.	2 refractory-lined cyclones, each 0.32m; other devices tried include Ducon granular bed filter, tertiary cyclone, Acurax bag filter.	3 cyclones in series. 200mm, 152 mm & 152 mm dia. respectively
Downstream Devices	1977-1980: Gas turbine. From 1981: on-line measurement of particulate and alkali metal content of hot combustion gas. No turbine.	Gas turbine.	Cascade from GE.	Low velocity (8m/s) and high velocity (240-420 m/s) gas turbine material test sections. LWTB is a long 10 cm dia pipe and WVTB has 4-six vane cascades. Alkali sampling train.
Major Investigations	Tests on combustion and emissions characteristics; erosion & corrosion resistance of materials for cooling tubes & turbine components; tests on feeding and ash removal systems; advanced hot gas clean up device tests.	Will investigate combustion and emission characteristics using multiple coal feed guns; scale-up effects on cyclone performance; erosion/corrosion of cooling tube and turbine materials; integrated control system and its responses to load change & dynamics events.	Sulphur capture with limestone & dolomite; combustion efficiency; dynamic response; particulate emissions, hot gas clean-up; NO _x emissions, sorbent regeneration. Some work also performed on 0.114 m bench unit.	Long timer (>10,000) test of erosion/corrosion/deposition for wide range of gas turbine materials exposed to high velocity PFBC hot combustion gas; hot gas clean-up and alkali removal.
Current Status or Work	Tests on hot gas clean-up devices will continue to the end of 1983. After that no further plans for this rig.	Work to begin in late 1983.	Decommissioned. Some work continuing in bench unit on hot gas clean-up.	More than 2000 hrs. of tests complete. Up to 10,000 hrs. of further testing planned during the next two years.

TABLE 2 - DETAILS OF MAJOR PFBC EXPERIMENTAL FACILITIES VISITED (Continued)

Organization	IEA (GRIMETHORPE)	NASA LEWIS RESEARCH CENTER	NEW YORK UNIVERSITY	STAL-LAVAL, AMERICAN ELECTRIC POWER, DEUTSCHE-BARCOCK
Location	Grimethorpe, Yorkshire, UK	Cleveland, Ohio, USA	New York, N.Y., USA	Malmö, Sweden
Operating Period	1981 - present	1974-79	1982 - present	1982 - present
Chamber Inside Dimensions (m)	2.0 x 2.0 x 8.0	0.23 to 0.47 (tapered) x 3 high	0.762 dia	tapered rectangular; 2 x 1 x 7
Chamber Cross-Sect. Area (m ²)	4.0	0.041 at bottom	0.46	2
Pressure Range (bar)	6 - 12	2 - 14	1 - 10 bar	18
Temperature Range (°C)	800 - 950	815 - 1037	740 - 980	830 - 980
Superficial Velocity (m/s)	0.75 - 3.7	0.7 to 2.6	up to 2	1.5 (bottom) - 0.9 (top)
Excess Air (%)	10 - 100	0.03 - 2.0	NA	30
Bed Depth (m)	3.5 - 4.5	0.7 - 2.5	3.7	4
Coal Feed Rate (kg/h)	to 17,000	4.5 - 36	91 - 1800	2100
Sorbent Feed Rate (kg/h)	to 13,000	to 9.0	12 - 280	400
Thermal Rating (MW _{th})	85	0.5	7	15.4
Start-up Method	Propane	Mat. gas overhead burner	Electrical heating of combustion air	Oil
Shell Dimensions (m)	4.0 dia x 14 high	2.9 high	1.21 dia x 6.2	approx 4 dia x 9 high
Refractory Type	Water-cooled inner walls	Brick two layer	Cast Grefco Altax 858 & CR2300	Water-cooled membrane walls, refractory in fireboard
Distributor	Multiple bubble caps	9 Bubble caps, each with 9 x 2 mm dia. holes	Perforated sandwich plate, 21 free area, cooled by air & water	Air "nozzles"
Solids Feeding System	Pneumatic feed of blended solids from lock hopper system via rotary valves; auxiliary compressor supplies 2.7 kg/s air at about 14 bar; 9 feed points; pressure drop & load cells used to monitor feed rate.	Side entry at 1 point; lock hopper and screw feeder; measurement using load cell.	1 entry point from side; lock hopper system with calibrated rotary feeder; conveying through 84 mm pipe at 9.1 m/s.	1 feed point; pneumatic feed through bottom from lock hopper system.
Coal top size (mm)	1.6 to 6.4	1.7	6	3.2
Sorbent top size (mm)	1.6 to 6.4	2.8	NA	3.2
Solids Discharge System	Downwards via pipe through distributor to Y-leg, then conveyed to quench vessel.	Bed and cyclone solids discharge into lock hoppers.	Bed and cyclone discharges into lock hoppers.	Pneumatic conveying to lock hoppers; some heat recovery from hot solids.
In-Bed Heat Exchangers	Horizontal tubes, two spacings.	36 rows of concentric horizontal tubes, 12.7 & 9.6 mm ES.	Vertical & horizontal tubes; 6 bundles, each bundle having 4 rows, of 42 mm dia. tubes; total surface of 12.7 m ² .	Water-cooled horizontal tubes in bed and as superheater; cooled walls also.
Hot Gas Clean-up Devices	2 stages of cyclones (1.2 and 1.27 m dia refractory-lined; slip stream to third and fourth cyclones.	1 concentric two-stage Aerodyne separator, 254 mm and 149 mm dia; ceramic filter also.	2 stages of refractory lined cyclones, dias. 457 and 305 mm.	3 stages of cyclones in series.
Downstream Devices	Cascade for slip stream. Turbine planned for Phase II.	Chrysler automatic turbine.	None.	Rotating blades, cascade.
Major Investigations	Combustion efficiency; scale-up; heat transfer; various coals and sorbents; gas emissions; erosion; cascade now installed.	Optimum conditions to minimize carryover; concentric cyclone performance; SO ₂ & NO _x emissions; gas turbine tests; erosion & corrosion of turbine blades.	Preliminary testing of equipment in progress. Some heat transfer work was completed on an earlier 0.3 m dia. x 3 m unit at pressures to 5 bar.	Testing and verification of components to be used in Tidd large-scale unit, especially solids feeding and discharge systems, cyclones, turbine blades, heat exchanger tubes, control & operating methods.
Current Status or Work	Studies on English coals complete; US high-S and Germany high-ash coals to follow. Phase II would involve turbine tests.	Decommissioned.	Studies planned on combustion of lignite & other low grade fuels, hot gas clean-up, heat transfer.	Early problems on the point of being overcome; one-year series of tests about to begin; afterwards, system available for other tests.

2.3 Other PFBC Facilities or Centres

Aside from the institutions visited, covered in section 2.2 above, and the work at B.C. Hydro, discussed in section 5.1 below, PFBC work is in progress or has proceeded in a small number of other centres. Those that we are aware of are as follows:

- (a) American Electric Power: Since 1976 American Electric Power (AEP) has cooperated closely with Stal-Laval Turbin. Deutsche Babcock Anlagen of West Germany joined the cooperative effort in 1980. The AEP/SL/DBA program is now nearing the end of its second phase. Testing work has been sponsored at Leatherhead and technical and economic studies have been completed on an engineering system development plant utilizing PFBC adjacent to the Tidd Plant of the Ohio Power Company and AEP System Company on the Ohio River at Brilliant, Ohio. The proposed facility would have a combined gas turbine and steam cycle output of 170 MW. A decision is expected in 1984 on whether or not to proceed with construction at Tidd. This decision will be influenced by the findings at the component test facility in Malmo (see section 2.2.11).

Detailed design work is also in progress on a 650 MW plant and conceptual work on a four-unit 2600 MW plant in Kentucky has also been reported (195). AEP is responsible for overall program direction, technological and economic assessment and integrated plant design in the joint work with Stal-Laval and Deutsche-Babcock.

- (b) Combustion Power Company: CPC operated an 8.7 MW_t facility for "adiabatic" operation in the early 1970's. It was used for burning garbage as well as coal. Sufficient excess air (up to 300%) was used at 5 bars that cooling coils were not required. The off-gases were cleaned in three cyclones and directed to a 1 MW_e turbine. However, plugging of cyclones and deposition on the turbine blades was severe. The third cyclone was later replaced by a moving bed granular filter. The unit has apparently been shut down since 1975 (3).
- (c) Deutsche-Babcock Anlagen: Deutsche-Babcock is a diversified German company with a major activity in the area of steam turbines. It has been developing AFBC boilers for some time and since 1980 has joined with Stal-Laval and American Electric Power (as discussed above) in developing PFBC. DBA's role in this partnership is the design of the fluidized bed combustor itself, the steam cycle and some other auxiliaries.
- (d) Delft University of Technology, The Netherlands: A small scale PFBC experimental program is apparently starting up at Delft funded by TNO, the Netherlands organization for applied scientific research. We were unable to obtain any information on the details of the experimental facility. Some modelling work on freeboard combustion was presented recently by this group (194).

- (e) Department of Energy, U.S.: D.O.E. has supported a number of studies of PFBC at Leatherhead and elsewhere. Of special interest are recent proposals from CURL to build a pressurized circulating bed and from G.E. to build a turbulent pressurized bed operating at 24 bar in response to a request for proposals involving advanced concepts. No decision has been taken on these proposals.
- (f) Electric Power Research Institute: EPRI has contracted out a number of studies in the PFBC area as well as being very active in AFBC development. For example, Brown, Boveri and Company recently completed an assessment of alternative PFBC cycles (157). EPRI recently issued a request for proposals on the low temperature turbo-charged boiler concept in the belief that this approach will allow problems with gas turbines to be sidestepped, while proving the reliability of the combustion process, control strategies etc. EPRI talks of implementing a commercial PFBC prototype within a decade if the tests at facilities such as Grimethorpe, Curtiss-Wright and Stal-Laval prove to be successful (195).
- (g) Gilbert/Commonwealth, Reading, Pennsylvania: This company does not have any experimental facilities, but has done several economic analyses funded by D.O.E. comparing different cycles (162) and alternative hot gas clean-up systems (170).
- (h) Hitachi, Japan: Our hosts at CURL reported that Hitachi may be becoming active in the PFBC field. No details are available.
- (i) University of Natal, South Africa: A 0.5 m dia by 4 m tall experimental PFBC unit to operate up to a pressure of 8 bars has been constructed recently at the University of Natal. The design is unique, using vertical tubes to form a draught tube, a conical base and internal cyclones. No reports of the performance of this unit appear to be available.
- (j) Technical University of Warsaw: A 6 bar, 0.3 m² PFBC unit equipped with a cascade of turbine blades has been constructed at the Institute of Power of the Technical University of Warsaw. A hot model of the PFBC chamber with tubes to be used for heat transfer studies was also constructed (3). Results from these units are awaited.
- (k) Westinghouse Electric Corporation: While Westinghouse has not operated any PFBC experimental facilities, it has maintained a close interest in this technology in addition to its activity in coal gasification and AFBC. Experimental studies have been conducted on hot gas clean-up and sorbent sulphation. Paper studies have dealt with such topics as cycle analysis, turbine corrosion/deposition and particle attrition.

3. PROBLEM AREAS IN IMPLEMENTING PRESSURIZED FLUIDIZED BED COMBUSTION

3.1 Cycles

From the point of view of overall cycle thermal efficiency, the key advantage of PFBC is that it enables a gas-turbine cycle and a steam-turbine cycle to be joined in a "combined-cycle" mode. This enables the high turbine inlet temperature of the gas-turbine cycle to be used in conjunction with the low temperature of heat rejection of the steam cycle leading to higher thermal efficiency. The overall efficiency of the combined-cycle operation may be several percentage points above that of a conventional pulverized-coal-fired steam cycle.

There are two basic schemes used for PFBC combined-cycle power generation; the air-tube cycle and the steam-tube cycle. Two versions of the air tube cycle are shown in Fig. 3.1. Air from the gas-turbine combustor is heated in heat exchanger tubes in the bed, and joins with combustion gases from the combustor before entering the gas-turbine. Hot exhaust gases from the final gas-turbine stage are used to generate steam for the steam cycle in a heat-recovery steam generator. The slightly more complex cycle shown in Fig. 3.1b uses gas-turbine exhaust gases to pre-heat combustion air as well as to generate steam in the heat-recovery steam generator.

A primary advantage of the air-tube cycles is that particulate-laden combustion gases are diluted with air before entering the gas-turbine, thereby reducing the risk of particulate erosion and corrosion of the turbine blading. On the other hand, the fact that gas-turbine exhaust gases are used to generate steam results in only moderate steam conditions of approximately 2.5 MPa and 400°C. Moreover, the in-bed tubes are at much higher temperatures, so that it is difficult to find a suitable tube material.

Two versions of the steam-tube cycle are shown in Fig. 3.2. In these cycles, the combustion gases pass undiluted through the gas-turbine, and steam is generated primarily using steam-tubes immersed in the fluidized bed. Gas-turbine exhaust is still used to pre-heat feed-water in the economiser. The cycle in Fig. 3.2b employs combustion air pre-heat and intercooling to raise the overall efficiency. The main advantage of the steam-tube cycle is that full conventional-plant steam conditions of 16 MPa and 540°C can be achieved, thereby raising the efficiency of the steam-cycle. A disadvantage is that high particulate loading onto the gas-turbine blading increases the risk of blade erosion and corrosion.

Figure 3.3 compares the overall thermal efficiency versus pressure ratio for the four cycles shown in Figs. 3.1 and 3.2. The steam tube cycles are seen to be more efficient than the air-tube cycles, but they operate at much higher combustor pressures for maximum efficiency. The substantially higher pressure (1.6 MPa) for the steam-tube combustor may be a disadvantage in designing the combustor pressure vessel.

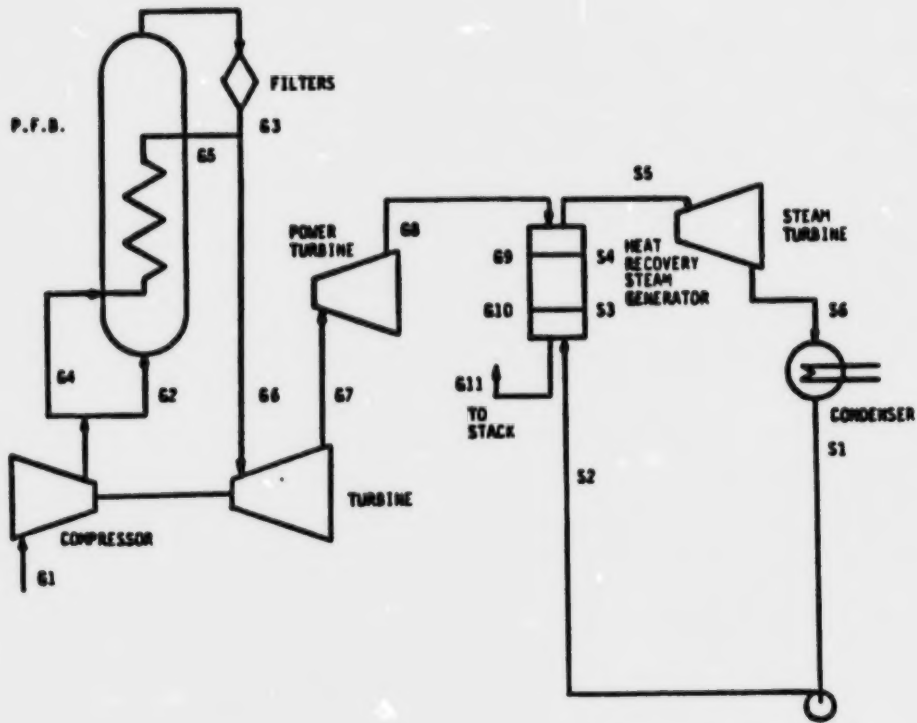


Fig. 3.1a: Basic Air Tube Combined Cycle

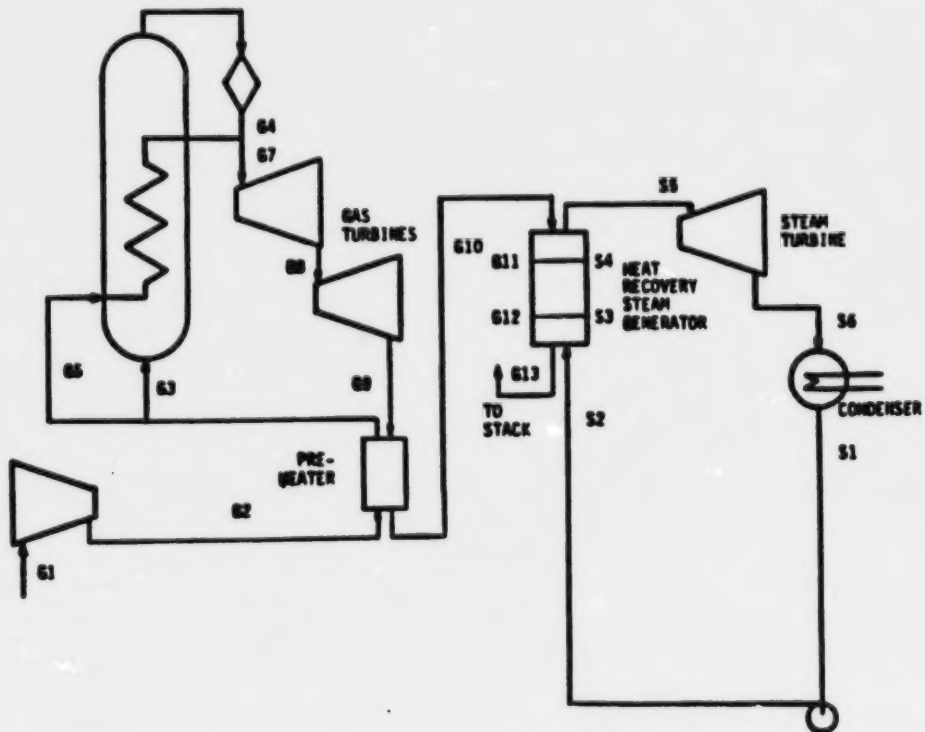


Fig. 3.1b: Air Tube Combined Cycle with Reheat

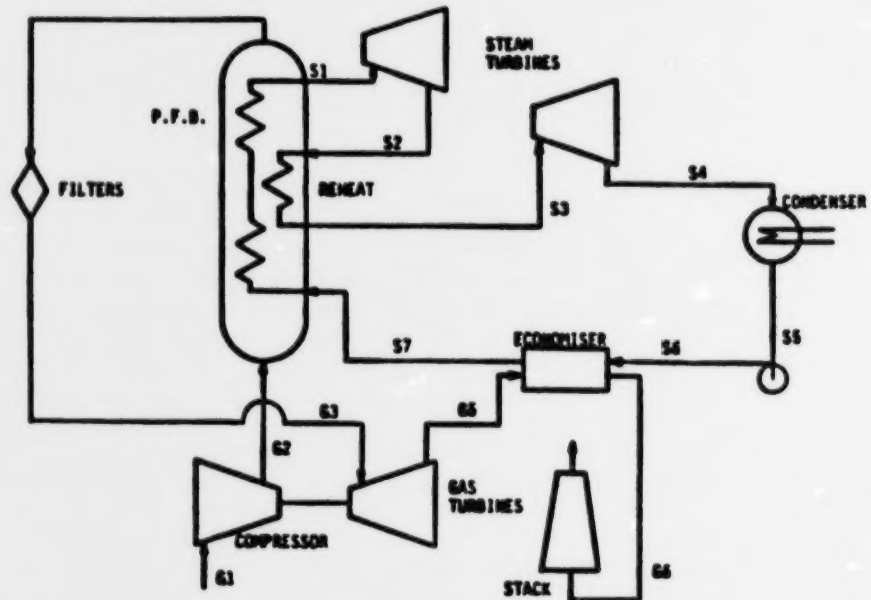


Fig. 3.2a: Basic Steam Tube Combined Cycle

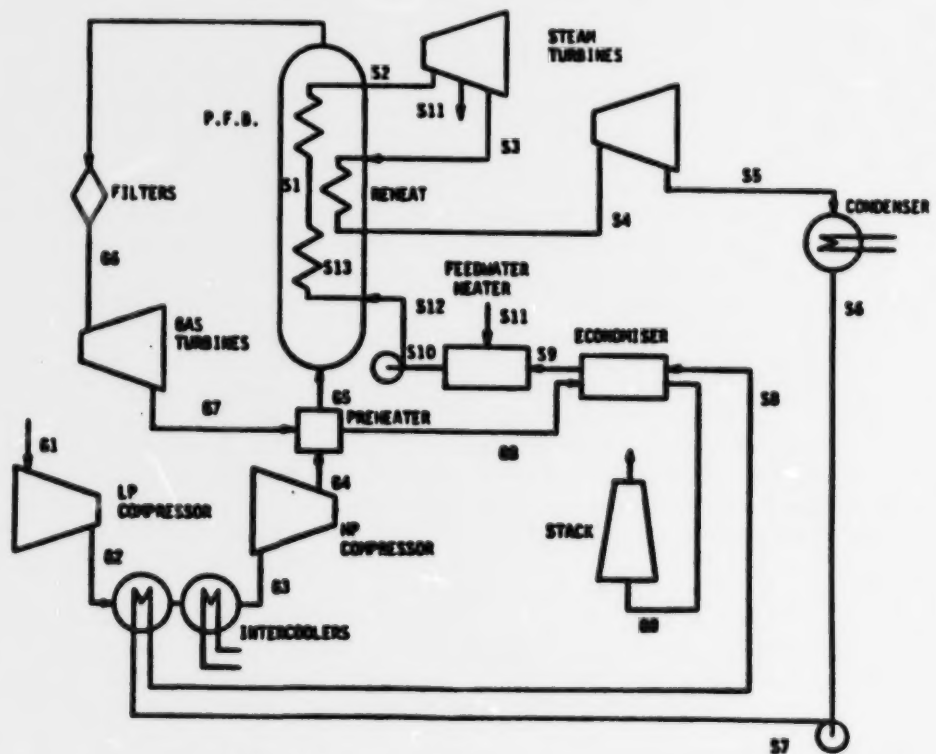
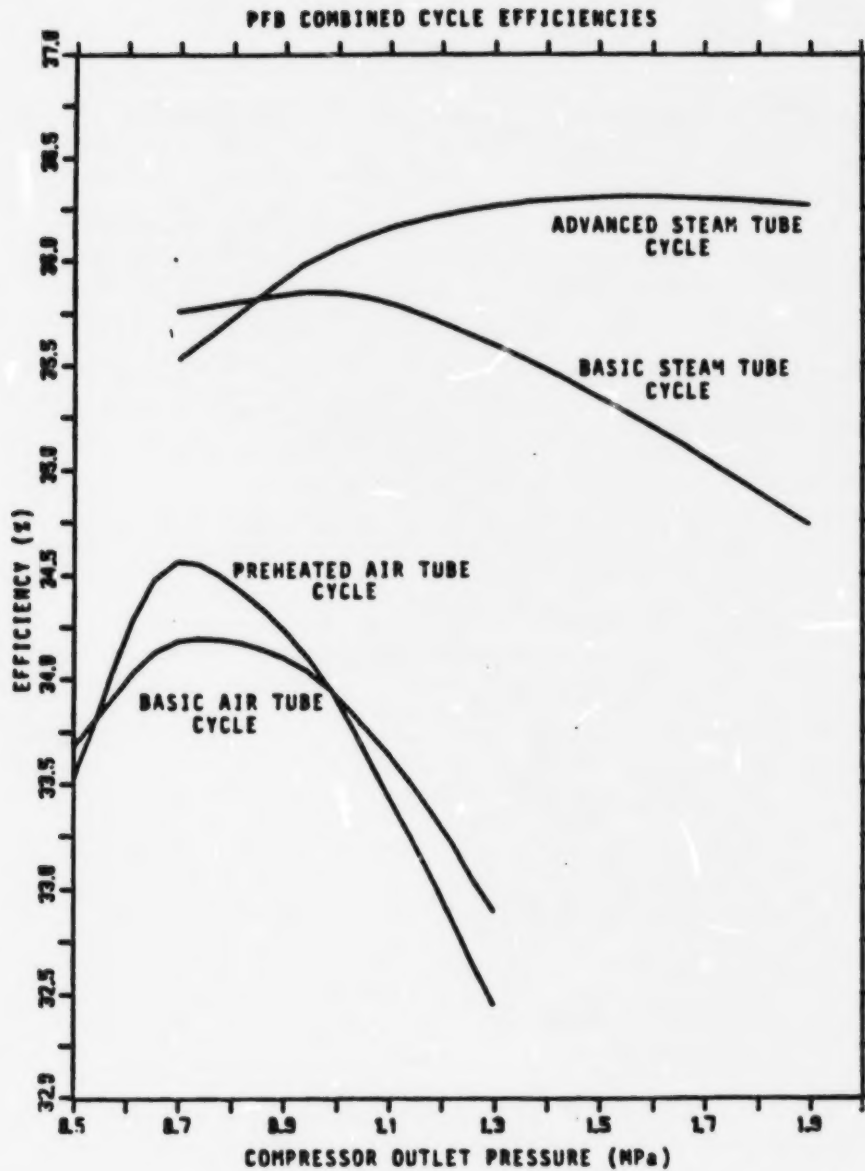


Fig. 3.2b: Steam Tube Combined Cycle with Preheat and Intercooling



Air Tube P.F.B. Temperature: 850 C

Steam tube P.F.B. Temperature: 800 C

Fig. 3.3: Efficiencies of Various PFBC Cycles as a Function of Operating Pressures

A major problem in utilizing either of the two types of combined-cycles with a PFBC combustor is likely to be system control. The interdependent nature of the two power cycles and the combustor will require a complex strategy. This control problem will be less severe for the air-tube cycles since the steam cycle is a heat recovery system, not directly linked to the gas cycle in the combustor. For the steam-tube cycle, however, the two cycles are linked in the combustor, resulting in a challenging control problem.

In a typical PFBC combustor the bed temperature will be limited to approximately 900°C in order to avoid ash-sintering problems and to permit efficient sulphur capture. The maximum gas-turbine inlet temperature must then be less than 900°C. This in turn means that PFBC cycles will not be able to take advantage of higher turbine inlet temperatures as gas-turbine technology advances, e.g. with the advent of ceramic or water-cooled turbine blades. This may put PFBC cycles at a disadvantage compared to coal gasification combined cycles, which could operate at state-of-the-art turbine inlet temperatures.

3.2 Materials, Erosion and Corrosion

Various materials have been tested both in the bed itself and downstream. Tests have involved bed components themselves, pins or coupons immersed in the bed, cascades, and turbine components.

(a) In-Bed Corrosion/Erosion:

In-bed corrosion of metal surfaces is primarily associated with oxidation/sulphation attack caused at low oxygen partial pressures and high local levels of SO₂ and SO₃. Local reducing regions, such as near coal feed points, are especially prone to attack. Start-up or upset conditions may also promote attack. A long incubation period may be required before corrosion becomes apparent, followed by rapid damage, so that very long tests (e.g. 10,000h) may be required to provide reliable tests for corrosion. In general, high chromium content alloys have behaved better than nickel-based alloys in tests completed.

Erosion of tubes and other elements due to the impact or abrasion of particles may also occur, and may combine with erosion effects. This damage is often found on the lower portion of heat transfer tubes, especially if these are near the distributor plate or near solids feed points. The tube wear encountered at Grimethorpe in recent tests (see section 2.2) is a dramatic example. Further work is required to elucidate the causes of this problem and to see whether geometries and tube spacings can be found which resist attack.

Refractory materials may also be subject to wear. The principal mechanisms of refractory attack are thermal spallation, carbon monoxide disintegration, alkali bursting and erosion. Refractories are already available that appear to offer long life under PFBC conditions.

(b) Turbine Blade Corrosion/Deposition

The economic viability of PFBC depends on reliable gas turbine performance combined with steam cycle performance. It is essential that gas turbine blades be able to withstand the gas produced by the combustor for prolonged exposures. These gases contain entrained particles as well as hot combustion products, SO_2 , SO_3 , chlorides, volatile alkali and trace metal species, produced not only from the coal, but also by the solid sorbent. Erosion, corrosion, deposition or some combination may occur, limiting the life expectancy and efficiency of the turbine.

Extensive tests have already been conducted, especially by General Electric at its own facility and in conjunction with Exxon and CURL. While early tests tended to give mostly encouraging results, more recent tests with high bed temperatures and a high-potassium dolomite (172,173) have shown significant corrosion attack after only 250 hours on most materials tested. It is clear that considerable long-term testing is required to choose the most resistant materials as well as to test ceramic blades or ceramic-coated blades and water-cooled or air-cooled blades.

There has been a significant divergence of opinion (3) on the concentration and size distribution of entrained particles that a gas turbine can withstand. Clearly experimentation with large scale systems is required to settle this question. In addition, deposition of fly ash and spent sorbent on the blades may be a significant problem, and experience is again lacking under operating conditions that relate closely to large-scale installations.

3.3 Solids Feeding

Feeding of coal and sorbent particles to the base of pressurized fluidized beds has commonly caused severe problems. Systems are required which operate in a trouble-free manner over extended periods of operation. While PFBC systems are much smaller than AFBC systems of comparable capacity and thereby require fewer feed points, multiple feed points will still be required for power utility systems.

Lock-hopper systems combined with pneumatic feeding have been used extensively in PFBC systems operated so far. The proprietary Petrocarb system has also been incorporated in many cases. Limiting the moisture and fines content of the solid materials appears to be a key requirement for successful feeding.

3.4 Solids Discharge

While less tricky than solids feeding, discharge of spent sorbent, ash and unburnt char from the bed has also proved to be troublesome in a number of installations. Lock-hopper systems have been widely used to let down the pressure for the discharging solids. In the early installations, solids were withdrawn by overflow, but this had the disadvantages of preventing variation in the bed level, removal of large agglomerates or rapid discharge of the bed during an emergency. Current methods use discharge through the bottom with valves or fluidizing air in the standpipe to control the discharge rate. Dry discharge is preferable, although slurry discharge has been employed at Grimethorpe.

Discharge of those solids caught by cyclones and not reinjected into the bed is universally accomplished via lock-hoppers. These systems generally perform in a satisfactory manner.

3.5 Hot Gas Clean-up

The erosion and deposition on gas turbine blades can be reduced greatly if particulate matter can be effectively removed from the off-gases. Corrosion may also be lessened if alkali and other gaseous components can be captured.

While cyclones are universally employed as the primary or primary and secondary method of reducing particulate loadings, a number of devices have been investigated in an effort to provide considerably enhanced removal efficiencies. These include:

- (i) high performance tertiary cyclones of various designs
- (ii) granular bed filters
- (iii) ceramic barrier filters
- (iv) fluidized bed filters
- (v) electrostatic precipitators

Further work is required to demonstrate the reliability and efficiency of these devices. While some encouraging results have been obtained, considerable further work is required to devise reliable control systems.

Some investigation has also taken place on the capture of alkali vapours. This may be accomplished, for example, in granular bed or fluidized bed filters that employ activated alumina or diatomaceous earth as the interceptor particles. Early work in this area was reviewed by Miller et al (3).

3.6 Gas Turbines

The major problem with gas-turbines operating in a PFBC combined-cycle is undoubtedly the particulate material from the bed impinging on the turbine blading. This particulate loading can cause both mechanical and chemical corrosion of the blade material. Buildup of deposits on turbine blading could also alter the blade profile, thereby substantially altering the aerodynamic performance of the blading.

In addition to the particulate material entrained in the exhaust gases, corrosive compounds such as alkali metal salts may result in severe blade corrosion. If these materials are not removed from the gases before the gas-turbine inlet, it could be necessary to reduce the turbine inlet temperature resulting in a lowering of the overall cycle thermal efficiency.

3.7 Other Problem Areas

The key problem areas are discussed above, while areas which have given relatively little trouble were discussed in section 2.1. While we have identified key problem areas, there are other matters on which design decisions must be taken which may have an important influence on the operation and cost of the unit. While they may not constitute "problem" areas in the same sense as the topics discussed above, the following questions require special consideration:

- What is the optimum orientation and configuration of heat transfer tubes?
- What is the optimum distributor plate design?
- Should the column be tapered or untapered?
- Should one employ a double shell construction or a single refractory-lined shell?
- What is the optimum regime of fluidized bed operation, i.e. fast fluidization, the turbulent regime, or the bubbling regime?

Some of these topics are discussed in Chapter 4 below.

4. PROMISING AREAS FOR FUTURE WORK

4.1 Advanced Cycles

With a complex combined-cycle, such as those used for PFBC power generation, the selection of equipment and unit sizes is critical to achieve maximum efficiency with a balanced cycle. This is particularly true when the off-design performance of these cycles is considered. In order to achieve an optimum configuration over a range of operating conditions, a thorough examination of many different arrangements and component sizes should be made using computer models before a final design configuration is chosen. Such computer modelling may well identify design modifications to the basic design which would improve design efficiency or operational flexibility. Examples of these modifications to the basic cycles would be the addition of regenerative feed-water heating to the steam cycle and inter-cooling to the gas cycle.

An advanced cycle which has been proposed in the literature is the re-fired air tube cycle. In this cycle, additional fuel is used in the heat-recovery steam generator in order to bring the steam conditions up to those of a conventional pulverized coal fired plant. The cycle then retains the advantages of the air-tube cycle while gaining the advantage of the steam-tube cycle in having much higher steam conditions. The re-fired steam generator could utilize an atmospheric fluidized bed or a conventional pulverized fuel boiler. Extensive modelling of this cycle would be required before an optimum system configuration could be chosen.

In section 3.1 it was indicated that control of complex PFBC combined cycles is a challenging design problem. The study of control strategies and control system design is an area where further development work should be carried out. In the first instance, different control strategies should be examined using computer models to evaluate the most promising alternatives. Various elements of the most promising strategies could then be examined in an experimental rig.

4.2 Circulating Pressurized Fluidized Beds

Considerable success has been shown in recent years in operating fluidized beds at such high superficial gas velocities (typically 6-10 m/s) that the bed ceases to have a distinct upper interface. Instead, the solids are continuously conveyed as a dense suspension up to the top of the vessel where they are returned via cyclones or by other means to the bottom of the column. Such "circulating beds" have been employed for many years in the calcination of alumina, and they have recently begun to find application for combustion of a wide variety of solid fuels including coal, peat, wood wastes, and tar sands coke. Advantages relative to bubbling AFBC units include improved sorbent utilization, reduced NO_x levels due to staged combustion, a smaller number of solids feed points, reduced cross-sectional area, improved turndown, and the ability to handle a wider variety of fuels. A 95 MW_e electric utility boiler is currently being designed for Duisburg, West Germany using the circulating bed principle (198), while a number of units of various sizes are in operation in Scandinavia for district heating and regeneration (199).

So far, all reported circulating beds operate under atmospheric pressure conditions. In principle, however, there appears to be no reason why the advantages of pressurized combustion cannot be combined with the attractive features of circulating beds in pressurized circulating fluidized bed combustion (PCFBC). The advantages of such a scheme have been discussed by Crouse et al (143). As noted elsewhere in this report, some work is already in progress in Sweden, and a proposal has been submitted by the CURL group for experimental facilities to test the feasibility of the PCFBC concept. If this work turns out to be successful, bubbling PFBC units could be displaced by PCFBC units. The turbulent regime should also be explored to see where it may also offer advantages.

4.3 Hydrodynamics and Heat Transfer of Pressurized Fluidized Beds

Transitions between the regimes of fluidization discussed in section 4.2 are not well understood, even at atmospheric pressure, and there is certainly too little information to allow one to characterize the flow regime, gas-solid contacting etc. of high pressure beds. Even in the bubbling regime, pressure is known to cause a significant reduction in bubble size, at least for relatively fine solids, but the nature of the hydrodynamic changes are not well understood. In order to design and operate pressurized units with confidence, especially if high velocities are to be used, experimental study is required. In addition, in order to specify the amount of heat transfer surface required, bed-to-surface heat transfer measurements are required under the same high velocity, high pressure conditions.

4.4. Ceramic and Cooled Turbine Components

As already noted, erosion, corrosion and deposition represent key problems for gas turbines operated on the off-gases from fluidized bed combustors. If flawless ceramic turbine blades could be produced, they would be almost immune from corrosion due to alkali or sulphur and very resistant to erosion by ash particles. Aside from the problem of manufacturing very uniform blades, their reliability would have to be established by testing, and they would have a low tolerance to shock.

Research into ceramic turbine blades is in progress in many countries, especially Japan, the U.K. and the U.S. While such blades would give a boost to the technical feasibility of PFBC, it must be recognized that they would have an even larger impact on gasification (followed by gas-burning) routes to power generation because of the high temperatures that could then be tolerated in the gas turbines. Hence, while it seems only a matter of time before such components are available, their overall impact on PFBC is uncertain. Nevertheless, this is clearly an area where research effort is needed. The alternative of developing air-cooled or water-cooled blades should also be pursued.

4.5 Hot Gas Clean-up

There has already been a significant effort to develop efficient, reliable and inexpensive methods of removing solid particles down to at least 10 μm , and preferably 5 μm , at temperatures of the order of 1200K. To be truly economic, it should be possible to re-use or continuously regenerate the clean-up device. It would also be helpful if the device

were simultaneously able to capture alkalis and/or chlorides while removing the particulate matter. Granular bed and fluidized bed filters appear to have the best long-term prospects, and their development should be encouraged.

4.6 Solids Feeding and Solids Discharge

As already noted, feeding solids to the bed and removing spent solids from the bed represent principal areas of practical difficulty in laboratory and demonstration PFBC units. Feeding problems are likely to be more serious in larger scale units where more feed points will be needed. Research is required to allow reliable transfer of solids to or from the bed. In addition, the 1 feed point per square meter criterion which has commonly been used as a rule of thumb for AFBC units has little basis of support there; tests are needed to establish the lateral mixing of solids as a function of pressure and to give a good basis for choosing the spacing between feed points.

4.7 In-Bed Measurements and Models of Bed Behaviour

In order to obtain a detailed knowledge of the chemical and physical behaviour of pressurized combustors, local measurements are required of species concentrations, temperature, pressure, voidage, velocity, etc. In many cases, it would be helpful to have time-varying measurements. Special probes or measurement techniques are required for these purposes. These must be sufficiently robust to cope with the hostile environment of the combustor and yet small or inobtrusive enough to interfere in a negligible manner with the bed behaviour. As already reported, a useful beginning has been made in this direction (167,196).

Models can also play a useful role if properly conceived and verified. While there are many fluidized bed reactor models, some of which have been devised specifically for fluid bed combustors, all of these have been established with AFBC units in mind. Because of the hydrodynamic, geometric and kinetic differences in pressurized units and the larger fraction of bed usually occupied by heat transfer tubes, new or significantly modified models are required for pressurized combustors. If verified by experimental study, these models can be useful in designing, optimizing and controlling the PFBC units.

4.8 Other Promising Areas

While the topics discussed above appear to be the areas of most immediate concern, there are a number of other research topics which could also be of importance in establishing the technical or economic viability of PFBC. These include:

- developing processes for regeneration of limestones and dolomites
- finding the optimum pre-calcination procedures for sorbents
- using fuels other than coal

- devising control strategies and turndown procedures
- investigating the effect of tapered walls and of tightly packed tube banks on solids mixing and bed behaviour.

Other areas, while important for PFBC, are of more general importance for fluid bed processing. These include:

- relative merits of horizontal vs vertical tubes
- optimum design of distributor plates
- improved correlations for entrainment and transport disengaging height
- improved understanding of the fluidization of large particles and of solids of broad size distributions
- hydrodynamics of bubbles and movement of solid particles in tightly packed tube banks
- forces on tubes in beds at elevated pressures.

5. CANADA'S ROLE IN PRESSURIZED FLUIDIZED BED COMBUSTION

5.1 B.C. Hydro

B.C. Hydro has undertaken studies of a 200 MW combined cycle power plant which would employ PFBC and Hat Creek coal. The plant would consist of a 60 MW gas turbine in combined-cycle operation with a 150 MW steam turbine. The efficiency of such a plant is expected to be approximately 2 percentage points greater than a conventional pulverized-coal-fired plant.

Several combustion tests with B.C. coal and sorbent materials have been and are being carried out at test facilities in the U.K. and the U.S. to investigate combustion efficiency, fluidization characteristics, elutriation and sulphur retention. Extensive computer modelling has also been performed to analyze the performance of the PFBC combined cycle process.

5.2 Other Potential Users

At the present time there are no other potential users in Canada who have taken an active interest in PFBC. Saskatchewan Power Corporation has examined combined-cycle power generation using coal gasification, but they are evidently not actively pursuing this option at the present time. In Nova Scotia there has been interest in atmospheric fluidized bed combustion, but no active work has been undertaken with PFBC, so far as we can discover. In principle, however, all the coal-using electrical utility companies in Canada are potential users of PFBC technology, once the commercial viability of the process has been proven. Because PFBC technology, unlike AFBC technology, is only likely to be viable if it involves large-scale power generation, it is unlikely that other (non-utility) users will be found in Canada, at least over the next twenty year period.

5.3 Research Needs

Because no two coals or sorbents are exactly alike, it is essential that experimental tests be carried out with candidate Canadian materials before PFBC equipment is designed or constructed in this country. Coals from Eastern Canada have very high sulphur contents, while thermal coals from Western Canada tend to contain large quantities of ash. Hence efficient sulphur capture and problems associated with handling and disposal of ash should receive special attention for Canadian coals. However, there would appear to be no problems that are unique to Canada in applying PFBC technology.

Aside from the need to test Canadian coals and sorbents and to pay special attention to high sulphur and high ash coals, it is important that Canada develop expertise in PFBC technology. While Canada currently lags behind such countries as England, Sweden, Germany and the U.S. in

exploring this new technology, it may not be too late to take a leading role. Several possible strategies which could be pursued by Canada in the PFBC field are as follows:

- I. Canada could continue to play a spectator role, keeping abreast of developments abroad and having all testing and design work performed in other countries.
- II. Canada, recognizing that PFBC work is expensive, could buy into outside work or cooperate with other countries. For example, it could participate in Phase II of the Grimethorpe project, develop other joint projects through IEA, or enter into bilateral or trilateral agreements with selected other countries to share costs of development.
- III. Canada could develop its own PFBC facility, probably on a modest scale given the costs. The facility would not differ greatly from other "conventional" PFBC facilities visited as part of this study and described in this report, but would provide a place for testing Canadian coals and materials and developing expertise.
- IV. Canada could try to jump beyond the current state of technology on an experimental scale by developing expertise in particular areas which are vital or may lead to decisive advantages. Examples could be in developing novel coal feeding methods, ceramic or cooled turbine blades, circulating pressurized fluidized beds, or novel gas-cleaning methods.

Strategies II to IV above are not necessarily mutually exclusive. For example, it may be possible to develop a Canadian PFBC facility at the same time as specializing in one or more area that could lead to significant technical and economic advances.

5.4 Specific Recommendations

Given the limited availability of oil and hydroelectric energy sources and the public mistrust of nuclear energy, it is imperative that Canada make use of its abundant coal reserves for electricity, steam and heat generation. At the same time, concern with acid rain and the need for efficient utilization of energy resources require that improved technologies be used for burning the coal. Pressurized fluidized bed combustion appears to be ideally suited for these purposes since it promises cleaner, more efficient utilization of a wide variety of coals and other possible fuels for electricity production or for co-generation of electrical power, steam and heat. The technology appears to be economically viable and large-scale PFBC units are likely to be installed in the U.S. and in Europe within the next decade, despite the general softening in electricity demand. Most components of PFBC systems have already been shown to be feasible on test facilities, with improved performance of some components and tests of gas turbine needed to establish the reliability, availability and long-term efficiency of PFBC power stations.

Given the probable commercialization of PFBC and its potential in the Canadian context, we advise against following strategy I. Canada is endowed with an abundance of coals and possible sorbents materials. In addition, this country has long experience in electricity generation and significant expertise in fluidization, materials science and other areas which are required for the development of this field. An active role in the PFBC field is, in our opinion, well warranted.

While strategy II has some attractions, we would advise that Canadian participation in foreign projects should not become the exclusive vehicle for Canadian PFBC effort. More experience can be gained by managing and operating at least one facility within Canada itself. On the other hand, we see much less benefit in building a facility which would essentially duplicate work going on elsewhere than in establishing a centre or funding research where new concepts are being explored. As a follow-up to this project and report, the UBC group will soon submit an unsolicited proposal to the Canadian government for work of an innovative nature.

6. CONCLUSIONS

Pressurized fluidized bed combustion is at the point where large-scale commercial development is possible. While some problems have been encountered such as tube wear and failure of solids feeding and withdrawal components, no insuperable problems have been encountered in the various PFBC installations visited. A key technical area not yet fully addressed is the operation of gas turbines on the off-gases and the optimum method of removing particulates from those gases. PFBC units, in addition to confirming that they can operate with higher overall efficiencies in the combined cycle mode with lower SO_2 and NO_x emission levels, will also have to demonstrate that they can be operated safely and reliably with maximum availability and turndown before the technique will be widely adopted.

This study and report have identified key technical problem areas. Four possible strategies that could be followed by Canada in addressing the PFBC area have been defined. While participation in multi-lateral facilities or in projects initiated by other countries is not excluded, we recommend that Canada develop some PFBC expertise of its own. This work should not duplicate facilities already in service or under construction in other countries, but should seek to develop new areas which could provide significant advances. Some of these areas are identified as developing novel coal feeding methods, ceramic or cooled turbine blades, circulating pressurized fluidized beds, or innovative gas-cleaning methods.

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